Perceptuo-Motor Coordination in Cerebral Palsy

by

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Declaration

I declare that this thesis has been composed by myself and that the work in it is my own.

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Abstract

The thesis examined the importance for movement control of perceptual information about the relation of the actor to the environment and about the actor's action capabilities and bodily characteristics. In four experiments it was shown that providing better information improves perceptuo-motor performance in Cerebral Palsied (CP) children.

The first two studies investigated whether CP and normal children find 'abstract' tasks more difficult than 'concrete' tasks. CP children were found to perform better on a concrete bang-the-drum task than on an abstract move-as-far-as-you-can task. The underlying movement kinematics were also different, although the movements involved in both tasks were indistinguishable by eye. Thus, improving information about the CP child's relation to the environment by making a task more concrete improves movement control.

The importance of perceiving one's action capabilities was studied in an interceptive timing task in which CP and nursery children were striking an accelerating ball. The results showed that both groups controlled initiation of the striking movements by the value of an optic variable tau specifying time-to-contact under constant velocity (thus treating the accelerating ball as if it was travelling at a constant speed). However, the affected hand of the CP children initiated the striking actions at a significant larger tau value, thus allowing for its relative slowness.

The children's striking movements were also analysed in more detail to test a theory of how deceleration and timing of the hand are conjointly controlled. Extending a theory of visual control of linear braking, it was hypothesized that intercepting an approaching ball correctly is achieved by perceptually regulating the striking movement so as to keep the ratio position of the hand/the rate of change of position of the hand (the tau function of the hand) proportional to the ratio position of the ball/rate of change of the position of the ball (the tau function of the ball). The data support the hypothesis and indicate that the value of the tau function of the hand is used in the perceptual regulation of action.

The findings of these experiments have important practical implications for perceptuo-motor learning, development and rehabilitation.

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Chapter 1

An Action Approach to Human Movement

(Part of the argument is published in: Van der Meer, A.L.H., & Van der Weel, F.R. (1992). The specificity of action in the analysis of movements. *Human Movement Science, 11*, 000-000.)

1.1 Introduction

In this thesis, an action approach to human movement is adopted that treats every organism as an open system, acting in relation with its environment (Ingold, 1989a). Taking this view, three sets of implications can be drawn out. The first has to do with the relative priority of processes over events. The second concerns the nature of an order that is founded on relationships. The third deals with the question of how we are to understand the interface between organisms and their environments. These implications will be developed in the present Chapter, and a number of experiments with hemiparetic Cerebral Palsied (CP) children will be reported (Chapters 2, 4, 5 & 6) which test the viability of such an action approach.

1.2 Events & Processes

Traditionally in theories of movement control every bodily movement represents a singular *event* in an action marked by its unique set of kinematic and dynamic features. Every action is understood as a combination of a number of isolated postures and movements. For instance, if I stand pouring a glass of wine, it is

assumed that the position of my hand is determined by the angle which it makes with my forearm, and my forearm with my upper arm, and my upper arm with my trunk, etc. Commonly these separate movement characteristics are studied in isolation to derive actions from them through abstraction, explaining them as the results of interactions of the separate bodily movements. Actions are accordingly seen to consist in aggregate of interactions between various postures and movements.

The alternative is to view pure bodily movements not as isolated entities wrapped up in an action, but as embodiments of an *action process* (Van der Meer & Van der Weel, 1992a). In this respect, movements exist only so far as they evolve in time, they cannot exist in isolation, but are always part and parcel of a process. Pure bodily movements can never be described in a single instant. In their performance the three modes of time - the past, present and future - form a whole which cannot be split into individual elements. The action process is fundamental, from which movements can be derived.

Furthermore, action processes are not patterns of interactions of movements as in the wine pouring example, but unfolding of relationships. The distinction between interactions and relationships is critical. Namely, a relationship involves a series of interactions over time, as in perceptuo-motor learning and development (c.f. Hinde, 1987). For instance, newborn babies wave their arms spontaneously in front of their eyes while supine. In an experiment by Van der Meer *et al.* (1992) it was suggested that while looking at their waving hands these infants learn about their own body dynamics and dimensions. It was concluded that onset of reaching, which normally 'emerges' at around 20 weeks of age, is not such a discontinuous milestone in perceptuo-motor development as is commonly believed, but follows on naturally from previous interactions between the infant's eye and hand. The act of reaching out for objects in the environment should therefore not simply be seen as a pattern of interactions between the child and the object, but as an unfolding of relationships that builds upon a previous history of involvement. A relationship, then, is neither

an event nor a simple concatination of events, but a process in continuous creation over time.

Experiments on the differences between (abstract) bodily movements and (concrete) action processes are studied experimentally in Chapters 2 and 4 of this thesis. In Chapter 2 the possibility is examined whether physically handicapped children find abstract tasks, such as extending the arm as far as possible, more difficult than concrete tasks, such as reaching to grasp an object. It was expected that these children would perform better on concrete tasks because of their relational character. Further, it was thought that concrete tasks generally have greater informational support about the child's relation to the environment which should enhance the childrens' performance.

1.3 Explicate & Implicate order

To recognise that bodily movements are best understood as aspects of an action process is also to appreciate that we cannot understand actions by simply adding up the constituent postures and movements, as one might understand the construction of a computer. In a computer, each part is built independently of the others, and interacts with the other parts only through some kind of external contact. But this cannot be said about an action process, in which each movement of the body takes shape in continuous relation to all other postures and movements, such that the form of the movement enfolds the entire system of relationships that have made it what it is.

Bohm (1980) refers to this kind of relational order in which everything, ultimately, is enfolded in everything else, as the *implicate order*, by contrast to the *explicate order*, in which everything is closed to every other, lying only in its own particular region of space and time and outside the regions belonging to other things. Consider the

following example adapted from Bohm. In a television broadcast, the visible image is translated into a time order, which is 'carried' by the radio wave. Points that are near each other in the visual image are not necessarily 'near' in the order of the radio signal. Thus, the radio wave carries the visual image in an *implicate* order. The function of the receiver is then to *explicate* this order, i.e., to 'unfold' it in the form of a new visible image.

What is described in this example is crucial for the understanding of the relation between action processes and pure bodily movements. Namely, pure bodily movements can only be understood through a process of explication of the implicate order in which movements emerge from an action process, or in other words, they can be understood via the metaphor of enfolding and unfolding. The kinematic features of two movement patterns could look indistinguishable to the analytical eye and yet the underlying action processes could be entirely different.

Because of the implicate nature of an action process, every movement of the body has a spatio-temporal form determined by the spatio-temporal form of its 'neighbouring' movements so that the whole has a specific relational structure. To give an analogy, all the conic sections, from ellipse to hyperbola, can be generated from a basic quadratic equation by changing the parameter values. But the parameter values do not on their own dictate the form of the curve, since one must also know the equation (Ingold, 1989a). Likewise, movements do not on their own dictate an action process, since one must also know the relational properties of the generative field within the action space.

1.4 Interface between Organism & Environment

How, then, should we regard the environment of the moving organism? What goes for the implicate relationships of pure bodily movements in an action process also

goes for the implicate relationships of action processes at the organism-environment interface. Action processes come into being and are maintained because of a perpetual interchange between the organism and its environment. They are generated at the interface. What is given initially is a continuous generative action space (Von Hofsten, 1987) within which action processes emerge as discernible, bounded entities.

The next stage in my argument is to show that organisms play, via their bodies, an active role in controlling movements, rather than relegating them to the status of passive vehicles who merely respond to perceptual information from the environment. Then, based on the active role of the body, I will argue that the perceptual information used in controlling movements always refers to both the environment as well as to the organism. Gibson's (1979) concept of affordances will be described as an example of how a perception theory that assumes the complementarity between organism and environment can be operationalized both conceptually and empirically.

The organism with its uniquely shaped body is always at the centre of every action process. The body, however, does not refer to some sort of determinate position in relation to external coordinates in Euclidean space, but to the laying down of the first coordinates, the anchoring of the active organism within its - implicate - environmental relationships. The body is in the environment as the heart is in the organism: it keeps all environmental relationships alive and with them, it forms a system. Neither the body nor the environment are extrinsic to the organism; rather these terms are mutually implicated. For example, a hummingbird does not wonder what to do with a flower, any more than it wonders what to do with its beak. The environment that is perceived, is always perceived in reference to the perceiver. Consequently, perceptual information has two referents, the perceiver and the environment. Gibson's (1979) ecological approach to visual perception provides, via

the concept of affordances, a framework that is particularly useful for understanding this relationship.

1.5 The Concept of Affordances

The environment is, literally, that which surrounds, and therefore presupposes something to be surrounded. Organism and environment form an inseparable dyad (Gibson, 1979), or as Lewontin (1982) puts it, there is no organism without an environment, and no environment without an organism. However traditional movement scientists are inclined to think of the environment as a world of nature filled with objects both living and non-living, both mobile and stationary, like a huge room cluttered with furniture and decorations. Following this analogy the ecological niche signifies a little corner of nature that an organism occupies, and to which it has fitted itself through a process of adaptation. If I remove a vase from an alcove in the wall, a niche remains for a small object that might appropriately fill the vacant space; by analogy it is implied that the ecological niche of an organism is independently specified by the essential properties of the environment. The trouble with this analogy is that it ignores the most fundamental property of living things, that with each organism there comes into being a particular field of implicate relational properties, which underwrites its subsequent development (Ingold, 1989b). The effective environment of an organism consists not of objects as such, but of the opportunities or hindrances they offer for the realization of its activities. Gibson (1979) expresses this idea nicely by designating the constituents of the niche as a set of *affordances*.

A general theory of affordances is thus a theory about the behaviour not of an individual but of an interactive organism-environment system. Therefore, an adequate

description of an affordance entails, like a description of pure bodily movements in relation to an action process, (a) specifying the *implicate* order of the relationships beween the organism and the environment and (b) explaining the implicate order of relationships in terms of an *explicate* order to provide more detailed information about the ecosystem.

Studies by Warren et al. (1984, 1986 & 1987) provide good examples of such a relational, but detailed description of affordances. For instance, in a study on the visual perception of the climbability of stairs an analysis of affordances is used that (a) utilizes methods of intrinsic measurement and dimensional analyses to describe the implicate relationships between organism and environment, and (b) scales relevant environmental variables to action system variables, to yield dimensionless body-scaled ratios known as pi numbers that characterize a particular organism-environment fit in more detail. In these analyses, the ecosystem of organism and environment is presumed to be implicately related. Then, from the continuous variation in the organism-environment relationships, relatively autonomous pi numbers are identified providing more detailed information.

Examples of more specific information in this type of analysis is the occurrence of *optimal points* for preferred states at which a given action is most comfortable or efficient (Warren, 1984), and the emergence of *critical points* at which the limits of an action are reached and a phase transition to qualitatively different action occurs (Warren & Whang, 1987). Similar dimensionless ratios between between environmental dimensions and body dimensions have been determined empirically to delineate critical boundaries for sitting on chairs (Mark & Vogele, 1988), and grasping objects by large and small adult subjects (Newell et al., 1989). Thus, the implicate specifications of the organism-environment fit determine what a given situation affords for action, and optimal and critical points of an affordance emerge out of a further explication of the ecosystem.

Let me now address the way perception of affordances develops in infancy. Infants do not detect and cannot utilise many affordances available to adults. Perception of affordances involves learning, especially during infancy when action capabilities undergo dramatic change. Because of these changes in action capabilities, infants must update their appraisal of their own body and skills at the same time that exposure to the environment is broadening. It is now known that infants are sensitive to visual information specifying affordances for a falling off place within a few weeks after crawling onset (Gibson & Walk, 1960; Bertenthal & Campos, 1984; Rader et al., 1980). Gibson et al. (1987) showed that young walkers preferred a rigid surface to a waterbed for traversal, and when forced to cross they crawled rather than walked over it, whereas crawlers did not behave differentially to the two surfaces. It has also been shown that prelocomotor infants are sensitive to visual information specifying affordances of apertures and obstacles, but that perception becomes increasingly differentiated after onset of independent locomotion (Carrol & Gibson, 1981).

Dramatic changes in postural control and manipulation abilities during the first year of life offer infants increasing possibilities for action with objects. This development provides infants with new opportunities to discover new affordances (Gibson, 1988). Through exploration, infants detect object properties with increasing specificity and learn to adjust their actions accordingly. For instance, they learn about the organism-environment fit as it relates to objects in their immediate surroundings - whether or not an object is within reach (Field, 1976; Gordon & Yonas, 1976; Granrud, 1986), whether it is rigid or squeezable relative to grip strength (Rochat, 1987; Rochat & Gibson, 1985) whether it produces sound when shaken gently or requires a hefty shake to make a noise (Palmer, 1989), and so on. In short, this developmental progression affects the discovery and utilization of affordances.

Taken together, the above studies give an indication how human affordances are perceived by adults and by young members of the species. What about the way in which physically handicapped people perceive affordances? Do handicapped people have problems perceiving affordances, or do they perceive affordances in relation to their own bodily characteristics and action capabilities? Anecdotal evidence on recent stroke patients suggests the former, namely that these patients misperceive affordances. This may prompt them, for example, to pick up a cup with their now affected hand, since they still perceive the cup as graspable for them, even though their handicap prevents them from manipulating it any longer. But what if the handicap was acquired before, during or just after birth. Since CP infants are born handicapped it can be argued that they learn to perceive affordances in relation to their handicap, taking into account their unique bodily characteristics and different action capabilities.

This question will be addressed in this thesis. A number of experiments with hemiplegic Cerebral Palsied children will be reported, which has the advantage that their unaffected side provides an relatively normal control performance with their affected side - an advantage of particular relevance when investigating the role of 'the body' in movement control. Furthermore, in normal, healthy people the relational way in which affordances are perceived and acted upon in the environment is not always obvious. Indeed, the integrated nature tends to elude us. It is often only when we investigate impaired movement behaviour that our usual mode of acting in the environment becomes clear.

In general, existing research on affordances reveals that organisms do perceive the relation between properties of the environment and their own action system. This provides an empirical basis for the direct perception of affordances rather than absolute environmental properties. Affordances are perceived in terms of *intrinsic information* which specifies environmental dimensions relative to the dimensions of

the observer in units of some body-scaled or, more generally, action scaled metric. Because of its potential for the theoretical and empirical research, the concept of affordances plays a central role in this thesis. It will not only serve as a conceptual guideline for designing experiments in which a tight fit between organism and environment is presumed, but it will also be used as a research tool to describe this intimate relationship in more detail.

A special type of affordance that specifies a certain temporal relationship between the organism and the environment is the optical variable tau (Lee, 1976, 1980, 1991, 1992a,b,c). The tau function is a property of a continuous changing optic flow field in which both the information about the layout of the environment *and* the information about the movement of the observer is directly specified (Gibson, 1966; Lee, 1976). The variable tau provides an adequate, relational description of time-to-contact with a surface or an object because it reflects the implicate relationship between the organism and the environment which also can be explicated to provide more detailed information about the fit.

In Chapter 3 an in depth account of Lee's (1991; 1992a,b,c) generalised concept of tau is presented as a theoretical basis for the remaining experimental Chapters. The experimental data of Chapter 2 are then analysed and discussed in more kinematic detail in Chapter 4. Special attention is directed towards the differences in performance between abstract and concrete tasks. Because of the different environmental circumstances and the varying amount of perceptual information in the two tasks it is expected that, although the pure bodily movements involved in the two tasks look indistinguisable by eye, different kinematic and dynamic movement characteristics will be found.

The important role of the body as a referential starting point in perceptuo-motor control is considered in Chapters 5 and 6. Chapter 5 investigates whether or not CP children scale perceptual information in terms of their own action capabilities and bodily characteristics when perceiving and acting. Specifically, it was investigated

whether CP children, in trying to hit a moving ball, would show a difference in timing behaviour between the affected hand and non-affected hand. A group of control children was not expected to show such difference between hands. In addition, the children were tested on a 'button press' condition. This time the children did not actually strike the ball with their hand, instead they pressed a button to activate a bat to strike the ball in time. Since there are no real arm movements involved in pressing the button, it was expected that timing performance will be more variable. In Chapter 6 the experimental data of Chapter 5 are analysed in more detail. Control of movement of the hand to the bat in relation to movement of ball to the bat will be presented in terms of the generalized tau theory.

Let me summarise my argument by recapitulating three reasons why a traditional view of movement behaviour cannot explain movement control. First, movement control is always part and parcel of an *action process*, consisting in the creative unfolding of relationships. Yet traditional theories of human movement deal only in events of interactions between pre-constituted, pure bodily movements. Secondly, the order of action processes is *implicate*, yet in traditional theories of movement control perceptuo-motor actions are only conceivable as an explicate order. Thirdly, action processes are generated within a *relational field* that subsumes the interface between the organism and its environment. Yet traditionally actions are regarded as the result of internal (schemata, programmes, physical properties etc.) and external (environmental) factors.

To remedy the deficiencies of the traditional paradigm, movement control should not be regarded as an outcome of a large number of interactions among discrete bodily movements, but in topological terms as the unfolding of a total generative action space. The concept of affordances in which the organism is presumed to be intimately linked with the environment, provide an excellent example, not only how such a relational view can be conceptualized but also how such a view can be operationalized in empirical terms.

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Chapter 2

Effect of Task on Movement Control in Cerebral Palsy: Implications for Assessment and Therapy

(Paper published with: Van der Meer, A.L.H. & Lee, D.N. (1991) in *Developmental Medicine and Child Neurology*, *33*, 419-426.)

Abstract *In order to examine the possibility that children with Cerebral Palsy (CP) find abstract tasks, such as extending the arm as much as possible, more difficult than concrete tasks, such as reaching to grasp an object, nine hemiparetic children with CP and 12 nursery school children were tested with both a concrete and an abstract task. The children with CP achieved a significantly larger range of movement in the concrete task, whereas the nursery school children showed no difference between tasks. Thus the CP children's poorer performance on the abstract task did not fully reflect their movement capability. This means that conventional neurological measurements of limb function in cerebral palsy, which mainly use abstract tasks or passive movements, will give an incomplete picture of the child's action capability.*

2.1 Introduction

An eight-year-old boy with cerebral palsy and restricted movement of the fingers is asked to bring together the tips of index finger and thumb but cannot get them closer than 10 mm. Immediately afterwards, however, the child has little difficulty picking up a pencil less than half this thickness with the same digits. Such differences in CP

children's performance on abstract vs concrete tasks are well known by rehabilitation professionals. However, the phenomenon has not been studied experimentally and the implications for assessment and treatment of cerebral palsy have not been analysed. In this Chapter an experimental study of the phenomenon is reported and the implications are discussed.

Concrete tasks differ from abstract tasks in the degree to which the required act is directed toward controlling physical interaction with the environment or with the person's own body, as opposed to producing movement for its own sake. In general, the more concrete the task, the richer the perceptual information for guiding the movement. Difference in performance in abstract and concrete tasks has also been commonly observed in ideomotor apraxia (Brown, 1972) and in patients with joint or peripheral nerve injury. However, only in the latter case has the phenomenon been investigated experimentally (Leont'ev & Zaporozhets, 1960). In these experiments the patients, who had restricted movement of the elbow or shoulder as a result of their injury, were required to raise either their whole arm or forearm (depending on the site of the injury) in four tasks which varied from abstract to concrete. The tasks were to raise their arm (1) as far as possible with eyes shut, (2) as far as possible with eyes open and the arm seen against a ruled screen, (3) up to a designated point on the screen, and (4) to grasp an object. Though the form of the arm movement was the same in each task, the amplitude of the movement increased monotonically from task (1) to task (4) as the task became more concrete.

Detailed clinical neurological measurement of perceptuo-motor dysfunction in cerebral palsy (and other disorders) is mainly made in abstract tasks (Brown *et al.*, 1987, Reddihough *et al.*, 1987, Bleck, 1987). Isolated movements such as abduction and adduction of the leg, flexion and extension of the wrist, pronation and supination of the forearm, are used for assessing limb movement. Tests measure quantities such as range, speed, and acceleration of movement, and muscle tone and power. But what if movement in abstract tasks is not a good reflection of the child's ability to move in

normal concrete tasks, as rehabilitation professionals commonly believe? If a child does, in fact, show a measurable difference in quality of movement depending on the degree of concreteness of the task, then understanding why this happens should give insight into the child's handicap and enable therapy to be improved.

To test whether cerebral palsied children perform better on a concrete perceptuo-motor task than on an abstract task requiring the same movement, an experiment was designed involving pronation and supination of the forearm, a movement that CP children tend to find difficult (Colton *et al.*, 1976; Patella & Martucci, 1980; Sakellarides *et al.* 1981). The question was would they be able to pronate and supinate the forearm significantly further in the concrete task? Normal children served as controls.

2.2 Method

Subjects

CP Children

A consultant at the local children's hospital referred to us nine children with congenital CP, diagnosed as hemiparetic, who were all of normal intelligence and ranged in age from 3 yr to 7 yr 4 mth (mean age = 4 yr 11 mth, sd = 18 mth). Of the seven boys, the right side of the body was affected in five; the two girls were both right side affected. Using Ingram's (1984) classification two of the children were severely affected rendering one hand almost functionless, five were moderately affected, and two mildly so.

Nursery Children

Twelve children served as normal control subjects. Eleven were right-handed and

one left-handed, as assessed by a separate study (Mathieson, 1992). The group constituted all the children in the relevant age group in the Departmental Nursery School. The five boys and seven girls ranged in age from 3 yr 5 mth to 5 yr 2 mth (mean age = 4 yr 4 mth, sd = 7.0 mth).

Apparatus

To measure the degree of pronation and supination in the forearm a rotation apparatus was designed (see Figure 1). A drumstick (37 cm long), with a parallel handle attached (1.25 cm diameter, 15 cm long), was mounted on a horizontal axle, so that the drumstick could be moved freely in the child's frontoparallel plane. The height of the axle was adjusted on a vertical pole so that when the child sat on a chair and grasped the handle the forearm was in line with the axle with the elbow at approximately 90°. Infrared light emitting diodes (l.e.d.'s, not shown in Figure 1) were fixed to the axle and to a point 2 cm from the head of the drumstick. They were viewed, from about the same position as the camera used to take the photograph in Figure 1, by a Selspot camera at 2.5m distance. The camera's optical axis was perpendicular to the plane of movement of the drumstick.

The Selspot data were recorded on a computer at 62 frames per second. Each session was also videotaped, using a video camera placed just above the Selspot camera to obtain a similar field of view. Two identical tambourines of diameter 20 cm were used as drums in the concrete task.

Figure 1. A cerebral palsied child taking part in the experiments.

Procedure

Each subject was run individually in three rotation conditions, presented in the following order:

Passive

The child was asked to hold the handle tightly while the experimenter rotated the drumstick back and forth in the elbow joint *(articulatio cubiti)* until passive resistance was felt. This measured the maximum amount of pronation and supination possible in the elbow joint.

Abstract

The child was then asked to try to do it on his/her own and was urged to turn the handle back and forth as far as possible.

Concrete

Finally, as a game, the child was encouraged to "bang the drums" alternately with the drumstick. Experimenters on each side of the apparatus lowered the drums progressively during the 20s Selspot recording time to facilitate optimal performance. The pronation and supination movements were of the same form in the concrete and abstract tasks.

The experiment comprised four sessions each lasting about 10 minutes. An individual session consisted of three experimental conditions - passive, abstract, concrete - run in that order. This order minimised the amount of verbal instruction and showed the children that the purpose of the task was to move the drumstick as far as possible. Post-hoc counterbalancing for statistical purposes was carried out to check for possible order effects (see Results section). In each condition an average of six pronation and six supination movements were recorded, resulting in a total, for each child, of 24 pronations and 24 supinations per condition per hand. Throughout the experiment, care was taken that the child's elbow was bent at approximately 90° to prevent additional rotation from the shoulder joint *(articulatio humeri)*, that the

forearm was in line with the axis of rotation of the drumstick, and that the fingers were closed tightly around the handle to prevent additional rotation in the hand.

Measures

The angle of the drumstick to the vertical was calculated on each Selspot frame from the coordinates of the images of the two l.e.d.'s (see Figure 2a & b). Figure 2b is a typical record of a cerebral palsied child continuously pronating and supinating without help, which most of the children could do. Here the measure of pronation movement was the angular difference between a maximum supination position and the following maximum pronation position; the measure of supination movement was from the maximum pronation position to the following maximum supination position. Occasionally, one of the CP children had difficulty in supinating adequately with the affected hand. In such cases, after the child had attempted to supinate, the arm was turned further by the experimenter to the maximum passive supination position and the child made the next pronation movement from there. In these cases, the measure of supination was from a maximum pronation position to the maximum supination position that the child reached, and the measure of pronation was from the maximum supination position reached with the experimenter's help to the following maximum pronation position attained by the child. The video record was inspected to make sure that the child had not loosened grip on the handle during a movement. Occasionally this had occurred, in which case the movement was rejected.

From these basic measures were computed the average pronation amplitude and the average supination amplitude for each child with each hand in the three experimental conditions. Each average was computed over about 24 values.

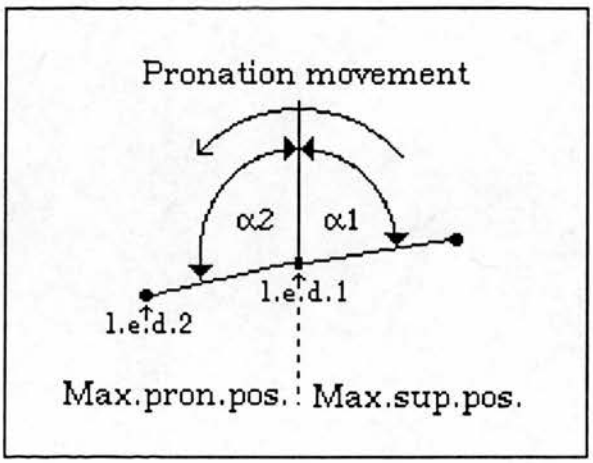

Fig. 2a

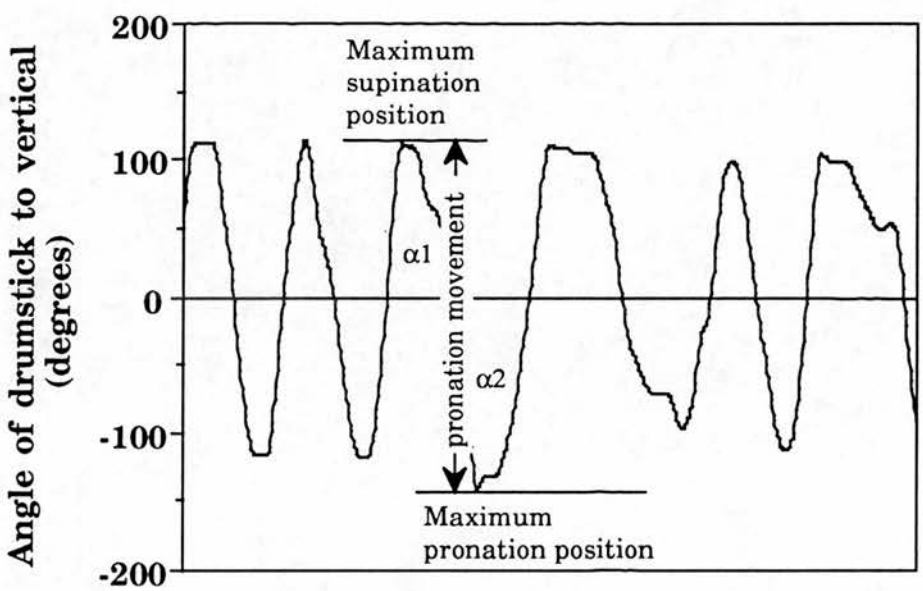

Fig. 2b

Figure 2. (a) Schematic representation of how the pronation and supination movements were measured. (b) Typical Selspot record of a moderately affected CP child continuously pronating and supinating during the 20s recording time. Note that a1 is the angle between the maximum supination position and the vertical; a2 is the angle between the vertical and the maximum pronation position.

2.3 Results

The mean results of the children's average pronation and supination amplitudes for each group of subjects in each condition are presented in Figure 3.

Effect of task

Movement range for the CP children was significantly larger in the concrete (drum) task than in the abstract task ($t(8) = 6.751$, $p < .0001$)[1], but the nursery children showed no difference ($t(11) = .659$, *ns*).

Qualifying this result, a mixed measures ANOVA (CP vs. nursery Group x abstract vs. concrete Task[2] x affected/non-dominant vs. unaffected/dominant Hand x pronation vs. supination Movement) reproduced the above two-way Task x Group interaction, $F(1,19) = 6.09$, $p < .025$. Eight t-tests showed that movement range was greater in the concrete task for the CP group only, especially for the affected hand (supination and pronation of the affected hand: $t(8) = 4.83$, $p < .002$ and $t(8) = 8.29$, $p < .0001$, respectively; supination and pronation of the unaffected hand: $t(8) = 2.11$, $p < .07$, *ns* and $t(8) = 2.43$, $p < .05$, respectively).

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[1] Post-hoc counterbalancing for statistical purposes was achieved by selective aggregation of sessions: for half the CP sample (randomly assigned), the abstract task of session 1, 2 and 3 was compared with the concrete task of session 1, 2, and 3 (any potential order effect favouring concrete); for the other half, the abstract task of session 2, 3, and 4 was compared with the concrete task of session 1, 2, and 3 (any potential order effect favouring abstract). A mixed measures ANOVA performed on these aggregated data showed that task order had no effect (main effect of Group was not significant, nor were any of the interaction effects involving Group).

[2] The passive task was not included in the ANOVA since we were only interested here in differences in self-produced movement between the abstract and concrete tasks.

The ANOVA also yielded a significant four-way interaction ($F(1,19) = 8.82$, $p < .01$). This interaction is due to the amplitude of pronation and supination differing only for the CP group in the abstract task with the affected hand.

Difference between hands

The movement range of the CP children was larger with the unaffected hand than with the affected hand, but the nursery children showed no significant difference

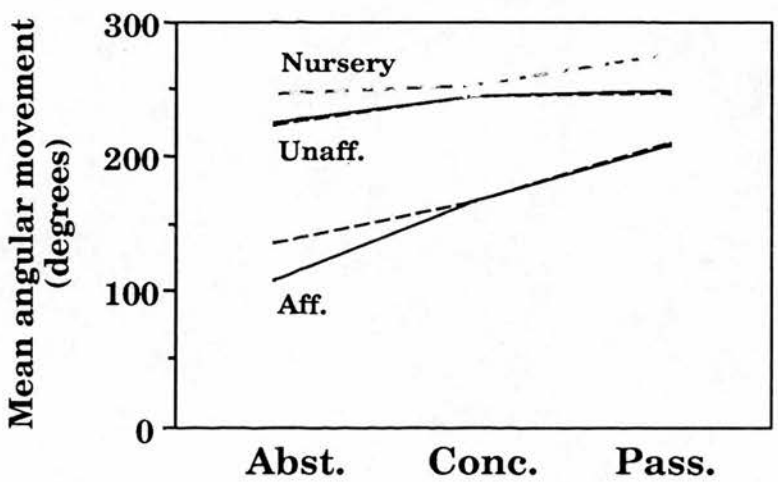

Figure 3. Means of pronation movements (dashed lines) and supination movements (solid lines) in the abstract, concrete, and passive rotation conditions for the nine hemiparetic CP children for each hand (affected and unaffected). The mean data for the twelve normal nursery school children are displayed combined (dotted line), since no significant differences between pronation and supination and non-dominant hand and dominant hand were found.

(Caption Figure 3 continued) Standard deviations: ***Nursery group*** *abstract, 28.40; concrete, 11.59; passive, 10.84;* ***CP group*** *abstract unaffected supination, 35.94; concrete unaffected supination, 15.59; passive unaffected supination, 14.30; abstract unaffected pronation, 33.76; concrete unaffected pronation, 15.29; passive unaffected pronation, 14.67; abstract affected supination, 87.90; concrete affected supination, 63.29; passive affected supination, 47.06; abstract affected pronation, 60.25; concrete affected pronation, 61.87; passive affected pronation, 47.84.*

between hands, as shown by the significant two-way interaction of Hand x Group, $F(1,19) = 19.26$, $p < .0004$. A significant difference was found between affected and unaffected hands in the CP group (supination, abstract: $t(8) = -3.706$, $p < .006$; pronation, abstract: $t(8) = -4.295$, $p < .003$; supination, concrete: $t(8) = -3.718$, $p < .006$; pronation, concrete: $t(8) = -3.873$, $p < .005$). None of the t-tests revealed a significant difference between the non-dominant and dominant hands for the nursery group.

Individual results

Each CP child showed a significant increase in the range of rotation in the forearm in changing from the abstract to the concrete rotation task for supination and pronation with the affected hand. Figure 4 shows the pronation and supination means for each hand as compared to the overall mean performance of the normal children. In supinating, all but one CP child increased the range of movement by more than 20% in going to the concrete task. In pronating, the same increase was found for seven out of nine CP children. The difference in the range of movement was sometimes pronounced. Four of the CP children, for instance, achieved a maximum supination of the forearm of less than 67° in the abstract task, but of more than 93° in the concrete task, i.e., an increase in range of 41% or more.

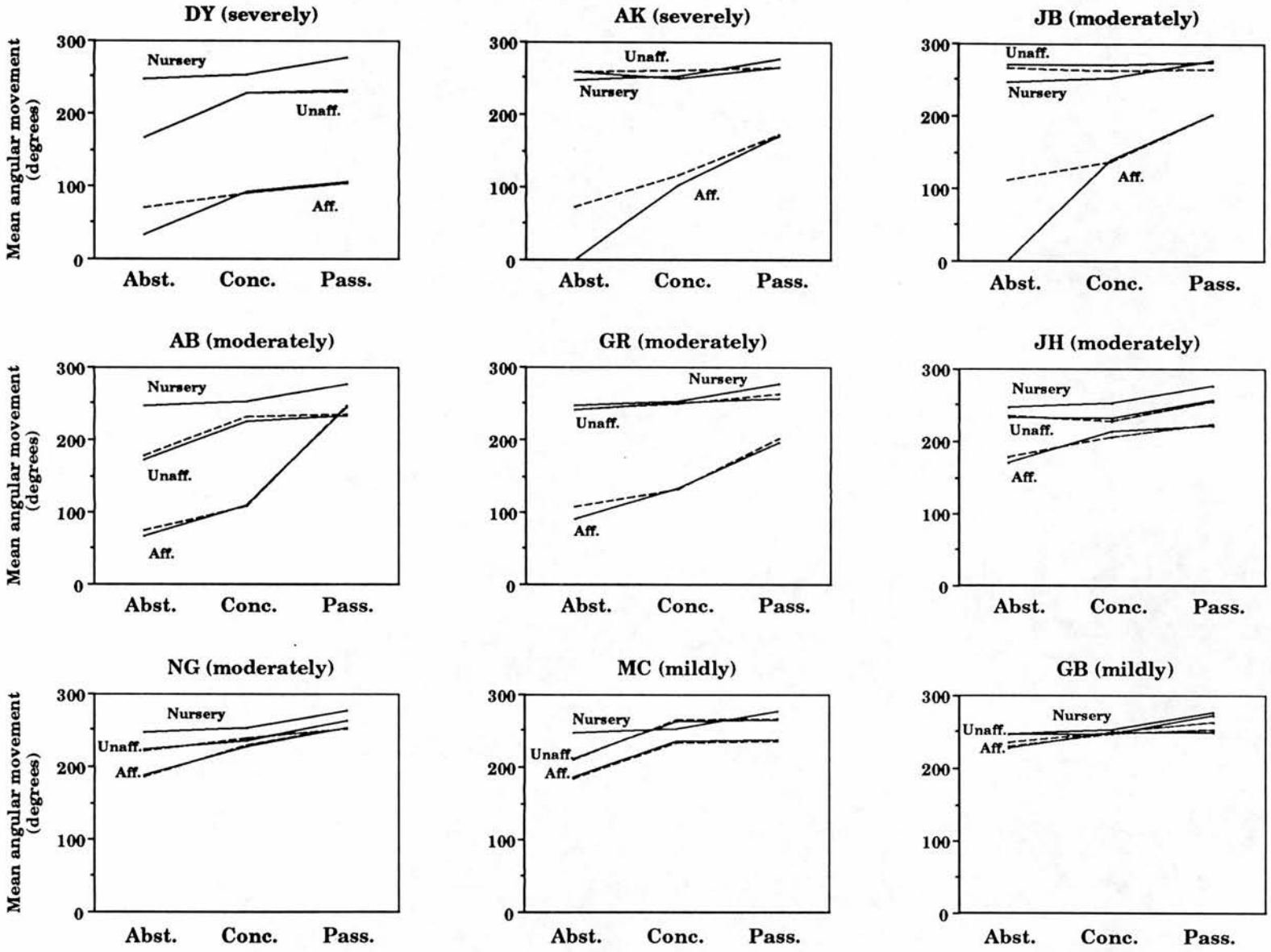

Figure 4. Pronation means (dashed lines) and supination means (solid lines) for each hemiparetic CP child for each hand (affected and unaffected) as compared to the overall mean performance of the nomal nursery children (dotted lines) in the abstract, concrete, and passive rotation conditions. According to Ingram's classification (1984), DY and AK were severely affected rendering the one hand almost functionless; JB, AB, GR, JH, and NG were moderately affected; and MC and GB mildly so. Note how the range of movement approaches that of the nursery group in going from the most affected to the least affected CP child.

2.4 Summary & Discussion

The hemiparetic CP children achieved significantly larger range of movement in the concrete bang-the-drums task than in the abstract move-as-far-as-you-can task. This applied to pronation and supination of the affected hand and to pronation of the unaffected hand. The movement range of the normal nursery school children, however, did not differ on the tasks. How can these results be explained and what are the implications?

Movement is not an independent process but is generally part and parcel of an act. Therefore, the range or quality of movement a person produces will depend not only on peripheral factors such as limits of muscular activity but also on the person's ability to perform the act in which the movement is being measured. That ability will, in turn, depend on factors such as how much practice they have had performing the act, their interest in performing the act and, last but not least, the quality of information that is available for controlling the movement. To take an obvious example of the importance of information, most adults are skilled at picking up a full glass and conveying it to their lips, but how many could carry out the same movement without the glass and not spill the pretend liquid? It takes much skill to make the same movement in the mime as in the normal act, because of the paucity of information to support the mime.

The factor discriminating concrete and abstract tasks is the degree to which the act required of the person is directed toward controlling physical interaction with the environment or with the person's body, as opposed to being directed toward producing movement for its own sake, as in performing the first position in ballet. Concrete tasks generally have greater informational support from the environment, as illustrated by the mime example. In the concrete bang-the-drums task, the movement was controlled by visual, auditory and tactile information about the child's relation to the drum, and the attainment of the goal of the act was readily

perceptible by the child. In contrast, progression toward the goal in the abstract move-as-far-as-you-can task could not be controlled by information about movement relative to the environment or to the body but had to depend on propriospecific information corresponding to sense of muscular effort or feel for limb configuration.

Therefore, a likely reason why the CP children performed less well in the abstract task is that the propriospecific information available to them in the abstract task was inadequate support for the act. Consequently, they could not demonstrate fully their potential for making the movement. This fits with a previous study, involving some of the same hemiparetic CP children as in the present study, which found proprioceptive deficiencies in the hemiparetic children (Lee et al, 1990). Poor proprioception could also explain the findings by Leont'ev and Zaporozhets (1960), cited earlier, that patients with joint or peripheral nerve injury were able to get higher when they were reaching to grasp an object than when they were simply trying to reach as high as they could. Providing better control information by making a task more concrete has been shown also to improve smoothness and coordination of movement both in hemiparetic stroke patients (Lough, 1985; reported in Lee & Young, 1986) and in patients with Parkinson's disease (Frischer, 1989).

Our findings have practical implications for measuring perceptuo-motor dysfunction in cerebral palsy. Most contemporary methods for measuring limb movement use only abstract tasks or passive movements (see Bleck, 1987). Our results show that measure of movement in a concrete task can reflect a child's ability to move better than the equivalent measure in an abstract task. Therefore, concrete tasks need also to be used in assessment in order to obtain a full picture of the child's ability. The difference in measures on abstract and concrete tasks should also help in making more detailed diagnoses regarding, for example, proprioceptive or other perceptual deficiencies. By these means it should be possible to accommodate the child with a therapy better tailored to his or her deficit.

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Chapter 3

Generalising Tau

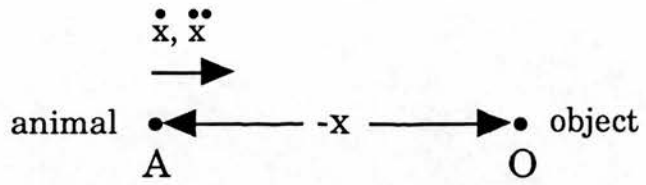
(The general theory of control of velocity of approach is also outlined in: Lee, D.N., Van der Weel, F.R., Hitchcock, T., Matejowsky, E. & Pettigrew, J.D. (1992b). Common principle of guidance by echolocation and vision. *Journal of Comparative Physiology,* in press.)

Abstract *A special type of affordance specifying time-to-contact with a surface or object under constant velocity is the tau variable. This optical variable was described in detail and its potential for controlling (velocity of) approach was outlined. The generalised tau theory served as a conceptual and empirical framework for the remaining experimental Chapters of this thesis.*

3.1 Introduction

Many perceptuo-motor actions require controlling velocity of approach to an object or destination, as when a pigeon lands on a perch (Lee, *et al.*, 1992a), when a bat flies to an aperture (Lee, *et al.*, 1992b) or when a driver stops behind another vehicle (Lee, 1976). In this Chapter a general theory of control of velocity of approach will be outlined. The implications of the theory are summarized in Figure 1 and details are given in Chapter 8 of this thesis (Appendix). To illustrate the theory a linear approach of an animal to a surface will be considered. The theory, however, applies to approach along any dimension - e.g., rotary approach along the angular dimension (Lee, *et al.*, 1992c).

(A)



(B)

Value of tau-dot ($\dot{\tau}$)	Implied movement of animal	Effect of keeping acceleration/ deceleration constant	Effect of keeping tau-dot constant
$\dot{\tau} > 1$	Accelerating	Collides ($\dot{\tau}$ decreases to 1)	Collides
$\dot{\tau} = 1$	Constant velocity	Collides ($\dot{\tau}$ constant)	Collides
$0.5 < \dot{\tau} < 1$	Decelerating	Collides ($\dot{\tau}$ increases to 1)	Controlled collision (braking increases)
$\dot{\tau} = 0.5$	Decelerating	Stops at	Stops at (braking constant)
$0 < \dot{\tau} < 0.5$	Decelerating	Stops short ($\dot{\tau}$ decreases)	Stops at (braking decreases)

Figure 1. (A) Notation for linear approach. At time t animal has coordinate x (<0) and is approaching surface with velocity x′ and acceleration x′′ (x′ = dx/dt, x′′ = d^2x/dt^2). Tau function of x = τ(x) = x/x′. Tau-dot = rate of change of τ(x) = τ′(x). (B) Summary of implications of theory of control of velocity of approach described in text.

3.2 The tau function

Suppose an animal is approaching a surface. Then the ratio of its distance away at any time to its speed of approach provides a first order estimate of its time-to-contact with the surface. If the velocity of approach stays constant then the ratio provides an accurate estimate, but if velocity decreases/increases the ratio under/overestimates time-to-contact. The ratio has been termed the *tau-margin* (Lee & Young, 1985). For the more general theory, the idea of the *tau function* is used. Suppose that a plane surface is being approached head on and the point aimed at is at the origin O. At time t we take the animal A to have coordinate x (<0) and to be approaching O with velocity x′ and acceleration x″ (Fig. 1a). Then the *tau function* of x is defined as x divided by its rate of change over time (x′). In symbols:

$$\tau(x) = x/x'$$

It has been shown that, in theory, the value of $\tau(x)$ is directly derivable from the optic flow field and does not need to be computed from information about distance and velocity (see, e.g., Lee, 1976 and Tresilian, 1990). Likewise, visual perceptual experiments using simulations of approaching surfaces have shown that the value of $\tau(x)$ can be perceived from the display without information about distance or velocity of the approaching surface (Schiff & Detwiler, 1979; Todd, 1981). Experiments indicate that optically-specified $\tau(x)$ is used to time interception of moving objects by humans (Bootsma & Van Wieringen, 1990; Lacquaniti & Maiolo, 1989; Lee *et al.*, 1983; Savelsbergh *et al.*, 1991) and to time locomotor actions of approaching surfaces by flies (Wagner, 1982), birds (Lee & Reddish, 1981), and humans (Lee *et al.*, 1982; Sidaway *et al.*, 1989; Warren *et al.*, 1986).

3.3 Stopping at an object

The rate of change with respect to time of $\tau(x)$ [= $\tau'(x)$ = tau-dot] is a dimensionless quantity which has the interesting property that it provides information for controlling braking. Control of braking to avoid colliding with a surface might appear to require computing appropriate deceleration on the basis of information about current distance from the surface and velocity of approach. However, this is not necessary. To avoid collision it is sufficient to register the value of $\tau'(x)$, adjust braking so that $\tau'(x) \leq 0.5$ and then keep braking constant. This procedure would generally result in stopping short of the surface (see Fig. 1b).

A general procedure to *stop at* a surface is to adjust braking so that $\tau'(x)$ stays *constant* at a value k, $0 < k \leq 0.5$ (Fig. 1b). Following this procedure requires steadily slackening off the brakes as the surface is approached (except for k=0.5 when deceleration is constant). Analysis of braking behavior of test drivers indicated that they followed the stop-at procedure with k = 0.425 (Lee, 1976).

3.4 Constant tau-dot approach

If $\tau'(x)$ is kept constant at a value k between 0.5 and 1.0 then braking has to get progressively *harder* as the object is approached. In fact, stopping at an object in this way theoretically requires reaching infinite braking force. A realistic procedure - the *controlled-collision procedure* - is to keep $\tau'(x)$ constant at a value between 0.5 and 1.0 until maximum braking power is reached, and then maintain this braking force. This would result in the animal colliding with the object but in a controlled way (Fig. 1b).

Film analysis of a hummingbird aerial docking on a feeder tube indicated it followed the controlled-collision procedure; as it braked it held $\tau'(x)$ constant at a

mean value of 0.71 and its bill passed into the feeder rather than stopping at the opening (Lee *et al.*, 1991). Similar results have been found for bats flying down a tunnel, slowing down to pass through a narrow aperture in the end to get a food reward. Analysis of their flight trajectories indicated they slowed down for the aperture by keeping $\tau'(x)$ constant (Lee *et al.*, 1992b).

An experiment with human subjects has shown (Kim *et al.*, 1991) that a person can judge from a computer simulation of approach to a surface with $\tau'(x)$ held constant at different values (but with no information about distance, velocity and deceleration of approach) whether the approach would result in a 'soft collision' ($\tau'x$) ≤ 0.5) or a 'hard collision' ($\tau'x$) > 0.5). It has also been shown that somersaulters on a trampoline control their landing by regulating body extension so that angular-tau converges linearly to zero at landing, at a rate between 0.5 and 1.0. In other words, angular-tau-dot is kept constant between 0.5 and 1.0 at a value equal to the ratio of angular-tau/time-to-landing (Lee *et al.*, 1992c)

In the remainder of this thesis the above theory of generalised tau will be investigated further. In particular it will be analysed how CP children and nursery children control approach of a rotating drumstick to a drum (Chapter 4) and of their hands to a bat in order to strike it (Chapters 5 & 6). Without compromising the tight fit between the organism and the environment, tau is shown to provide detailed information about both normal and handicapped movement behaviour.

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Chapter 4

The Important Role of Information for Perceptuo-Motor Learning

Abstract *The experimental data (obtained in the experiment reported in Chapter 2) of pronation and supination movements of one Cerebral Palsied child were analysed further in kinematic detail. Three variables: velocity profile, phase plane plots and angular tau-dot were compared between the abstract and the concrete rotation task. The results showed that although the movement patterns involved in both tasks are indistinguishable by eye, underlying movement kinematics were radically different. It was concluded that because of the varying degree of informational support from the environment the movements in the two tasks were controlled differently. The implications for perceptuo-motor learning were outlined.*

4.1 Introduction

In a study by Van der Weel et al. (1992; see also Chapter 2) it was found that Cerebral Palsied children pronated and supinated their forearm significantly further in a concrete bang-the-drum-task as opposed to an abstract move-as-far-as-you-can-task. That is to say, the amplitude of the pronation and supination movements was significantly larger in the concrete task than in the abstract task. The experiment reported here is a small pilot study conceived to investigate not whether the *result* of the pronation and supination movements was different between the two rotation

tasks but, whether underlying movement kinematics were also different, although the movement patterns involved in both tasks were indistinguishable by eye.

In studying consecutive hammer strokes Bernstein (1967) reported that when driving a nail into wood, subjects never produced the same movement twice. Thus, although movement outcome was identical across strokes - the nail was hit - never the same movement kinematics leading up to the hit could be observed. From this Bernstein formulated his important principle of non-equivocality: movement outcome is repeated with varying movement characteristics. This principle has important consequences for learning new perceptuo-motor skills, namely it implies that when practising new skills, the movements involved in the skill have to be made twice. In other words, the movements involved in the skill to be practised with as much variety as possible. Bernstein described this principle of perceptuo-motor learning as: repetition without repetition.

However, when learning new perceptuo-motor skills it is not only important that movements within the skill are practised with wide variety, as Bernstein correctly pointed out, but also that these movements are practised in an equally wide variety of relevant environmental circumstances. That this is indeed important has been shown in a study by Winold et. al. (submitted). In this study, the movement kinematics of playing a musical instrument were studied as reflected in the coordination of elbow, wrists, and bow of skilled cellists as they perform various musical fragments at different speeds, dynamics, and musical intention. It was found that the coordinative solutions to slow movements were not the same as those used for fast movements.

Thus, performing the same task in different environmental circumstances produces different movement kinematics. In this study this hypothesis was tested further. Movement characteristics of pronation and supination movements of a Cerebral Palsied child were examined in kinematic detail. In particular it was investigated whether movement characteristics in a concrete bang-the-drum-task task are different from those in an abstract move-as-far-as-you-can task.

4.2 Method

Subject

The experimental data collected in Chapter 2 were used again in the present study. From the data records one CP child (NG) was selected for further analysis. The child was a six-year-old girl and was diagnosed as having mild (Ingram, 1984) hemiparetic Cerebral Palsy. Her right hand side was affected. In the experiment in Chapter 2 she showed near normal performance in pronating and supinating the forearm.

Apparatus & Procedure

To measure the pronation and supination movements in the forearm the same rotation apparatus was used as in Chapter 2. Only data obtained in the abstract and concrete rotation tasks were used for further analysis. In the abstract task, the child was urged to turn the handle of the drumstick back and forth as far as possible in the elbow joint. In the concrete task the child was encouraged to "bang the drums" alternately with the drumstick. The pronation and supination movements were of the same form in the concrete and abstract tasks.

Measures

To measure the children's pronation and supination movements, infrared light emitting diods were attachted to the head and to the axle of the drumstick. The Selspot system scanned the camera image of the diodes and digitized their (x,y) coordinates. A computer recorded the coordinates at a sample rate of 62 Hz.

The angle of the drumstick to the vertical was calculated on each Selspot frame from the coordinates of the images of the two l.e.d.'s. The measure of pronation movement was the angular difference between a maximum supination position and the following maximum pronation position; the measure of supination movement was from the maximum pronation position to the following maximum supination position. From these basic measures were computed: velocity profiles, phase plane plots and angular-tau.

4.3 Results

Kinematic variables

Velocity profile

The angle coordinates of the drumstick to the vertical were differentiated to obtain velocity profiles from which were determined, (a) the start of the pro/supination movements, T(movement starts), (b) the peak velocity of the pro/supination movements, T(peak velocity), and the end of the pro/supination movements, T(movement ends). From these measures were computed the duration of acceleration ΔT(movement starts, peak velocity), the duration of deceleration ΔT(peak velocity, movement ends) and the total movement time ΔT(movement starts, movement ends) for each hand in the two experimental conditions (see Figure 1).

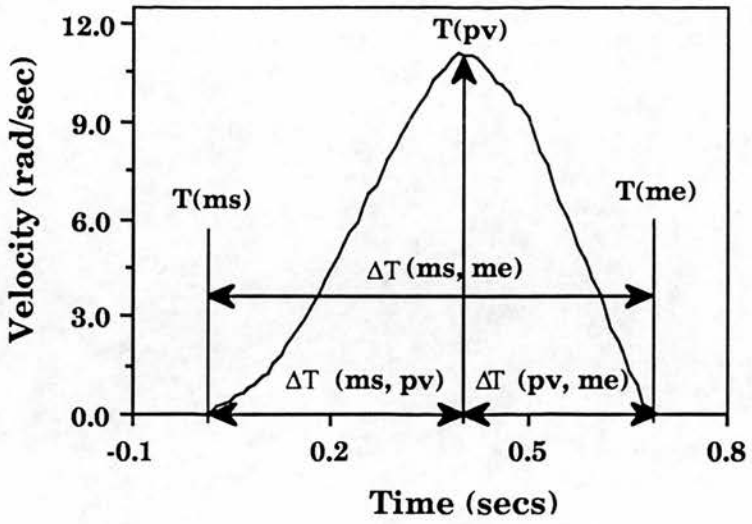

Figure 1. Schematic representation of how duration of acceleration phase ΔT(movement starts (ms), peak velocity(pv)), deceleration phase ΔT(peak velocity, movement ends(me)) and total movement time ΔT(movement starts, movement ends) were determined.

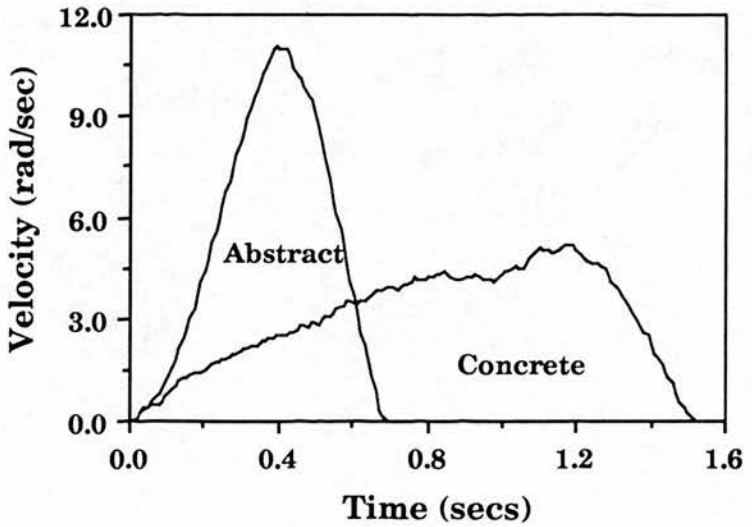

Figure 2. Typical velocity profiles of the subject supinating the forearm in the abstract and the concrete rotation task. Note that in the abstract task both the acceleration phase and deceleration phase have similar shapes, while in the concrete task the acceleration phase is longer than the deceleration phase.

The velocity profiles of pronation and supination movements, with the affected and non-affected hand in both the abstract and concrete rotation tasks are represented schematically in Figure 3. The shapes of the profiles look similar for the affected and non-affected hand and for pronation and supination movements. The velocity profiles in the abstract and concrete rotation tasks, however, look different. The acceleration phase and the deceleration phase in the abstract rotation task are of equal length, while in the concrete rotation task the acceleration phase is much longer than the deceleration phase. Total duration of acceleration and deceleration phase together is longer in the concrete rotation condition, and reaches a lower maximum velocity. The following analyses will examine these differences in more detail.

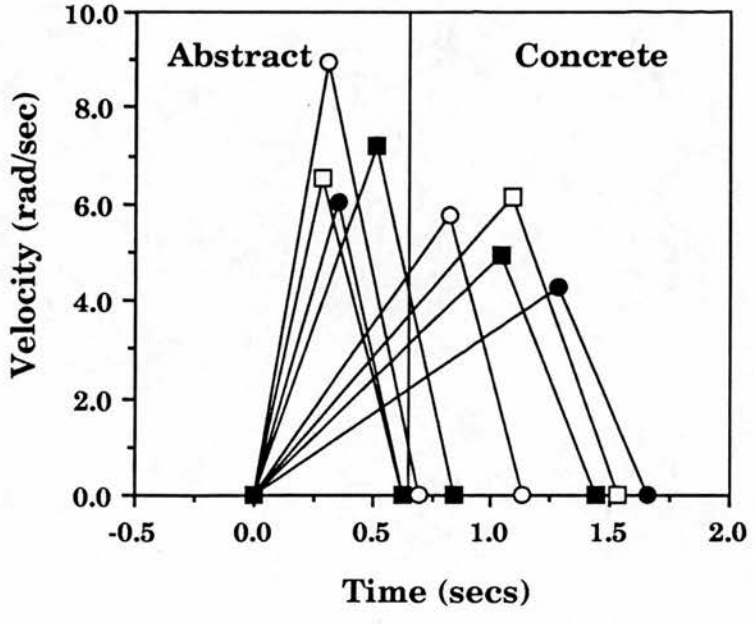

Figure 3. Schematic representation of velocity profiles for pronation movements (circular symbols) and supination movements (square symbols) for the affected hand (open symbols) and non-affected hand (closed symbols) in both the abstract and concrete rotation task.

Acceleration phase, ΔT(movement starts, peak velocity)

An analysis of variance (Task x Hand x pro/supination Movement) carried out on ΔT(movement starts, peak velocity) revealed a significant main effect of Task ($F(1,4) = 375.47$, $p < 0.0001$), showing that the building up of velocity to its maximum took significantly longer in the concrete rotation task.

Deceleration phase, ΔT(peak velocity, movement ends)

An ANOVA (Task x Hand x pro/supination Movement) carried out on ΔT(peak velocity, movement ends) showed no significant main effects, nor were any of the interaction effects significant.

Movement time, ΔT(movement starts, movement ends)

The analysis of variance (Task x Hand x pro/supination Movement) on ΔT(movement starts, movement ends) showed two significant main effects, that of Task ($F(1,4) = 583.08$, $p < 0.0001$) and Hand ($F(1,4) = 9.39$, $p < 0.05$). Observation of the individual means revealed that movement time was longer in the concrete task and that it was also significantly longer for the non-affected hand than for the affected hand.

Peak velocity, T(peak velocity)

Finally, an ANOVA (Task x Hand x pro/supination Movement) performed on T(peak velocity) showed two significant main effects namely that of Task ($F(1,3) = 11.24$, $p < 0.05$) and Hand ($F(1,4) = 32.25$, $p < 0.05$). This indicates that peak velocity was higher in the abstract rotation task and that the affected hand reached significantly higher peak velocities than the non-affected hand.

Phase plane plots

Consecutive pronation and supination movements of the forearm can be regarded as cyclical movements and can also be described by considering their displacement and velocity simultaneously as a vector. Displacement corresponds to the change in position over time, whereas velocity corresponds to the speed and direction at which that position is changing (Abraham & Shaw, 1981). The relation between these two variables is nonlinear, but can be captured using a phase plane diagram in which displacement is plotted on the x-axis and velocity is plotted on the y-axis (see Figure 4). In essence, a phase plane plot is a picture of the resultant action of the control mechanisms (Winstein & Garfinkel, 1989).

Figure 4 provides exemplar phase plane plots for pronation movements (below horizontal zero line) and supination movements (above horizontal zero line) of the child's affected hand in both the abstract (Fig. 4a) and concrete rotation task (Fig 4b). In the abstract rotation task, the phase plane plots of supination movements were circular shaped while the trajectories of pronation movements were more oval shaped and appeared less smooth. Range in velocity was higher for supination movements and was reached when the drumstick approximately passed the vertical.

In the concrete rotation task, the phase plane plots of both supination and pronation movements were oval shaped. Range in velocity was again higher for supination movements. Comparing the pro/supination movements between the abstract and concrete rotation tasks, the movements in the concrete task show a greater range of movement (cf. Chapter 2). Range in velocity, however, is greater for movements in the abstract rotation task, with greater differences between the abstract and the concrete task for supination movements.

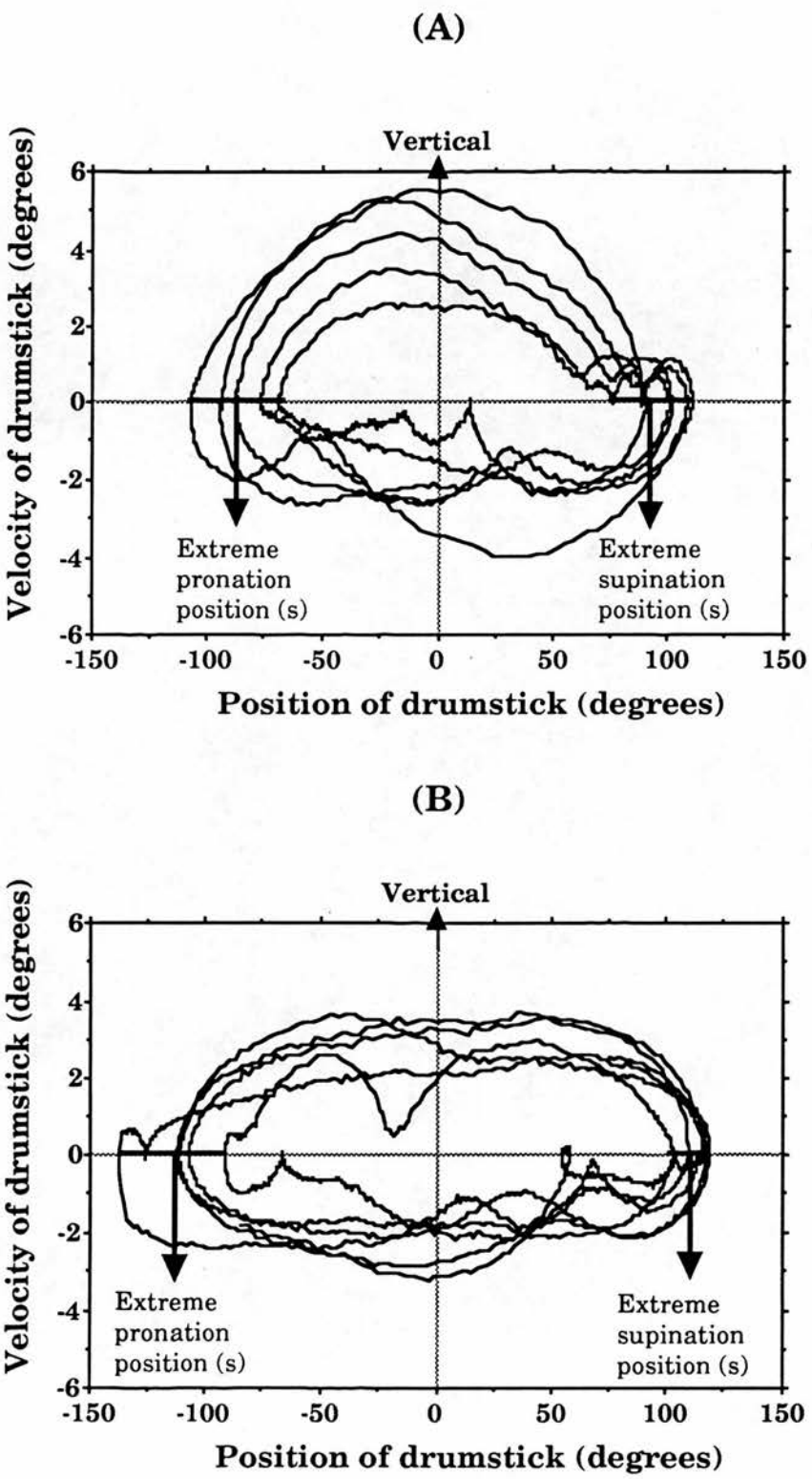

Figure 4. Typical phase plane trajectories of drumstick position against velocity for pronation and supination movements in the abstract (Fig. 4a) and concrete (Fig. 4b) rotation condition during the 20s Selspot recording time.

Angular tau [1]

The foundation of vision is the optic flow field (Lee, 1980), the changing pattern of light reflected from the environment to a moving eye. A flow property of wide application for action is the*tau* function of separation of image points, because it equals the tau function, $\tau(X)$, of the separation, X, from a point on a surface being approached. $\tau(X) = X/X'$ (where X' is the rate of change of X) equals time-to-contact under constant velocity. Experiments indicate $\tau(X)$ is, in fact, used under both constant and changing velocity: by plunging gannets to trigger streamlining (Lee & Reddish, 1981); by flies to trigger deceleration when landing (Wagner, 1982); and by humans to regulate step length when negotiating irregular terrain (Warren, *et al.*, 1986), to time preactivation of leg muscles when landing from a fall (Sidaway, *et al.*, 1989) and to time interceptive actions like hitting a ball (Lee, *et al.*, 1983; Chapter 5).

The *rate of change* of $\tau(X)$ [= $\tau(X)'$ = tau-dot] provides information for controlling approach. Information about distance, speed, and deceleration are not necessary (Kim, *et al.*, 1989; Schiff & Detwiler, 1979): to stop at a location, it is sufficient to keep *tau-dot* constant at a positive value not greater than 0.5, as experiments indicate test drivers do (Lee, 1976). The course of action results in deceleration being monotonically decreased and speed being zero as the location is reached (see Chapter 3, Fig. 1). If tau-dot is kept at a value greater than 0.5 (and less than 1.0), then deceleration will monotonically increase until, in practice, a maximum is reached.

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[1] For a full description of the generalised tau theory see Chapter 3 and Chapter 8 (Appendix).

Controlling rotation in the forearm

Applying the theory of a constant tau-dot approach now to the control of rotating the forearm, it is hypothesized that when pronating and supinating the forearm the child keeps the rate of change of deceleration of the moving arm constant when approaching the extreme pro/supination position. One might of course argue that rotating the forearm towards the extreme pro/supination position does not require any specific control mechanism because the child just 'bangs' the arm over and is stopped by muscles, ligaments and joints. However, it is crucial that 'collision' be controlled so as to avoid injury. For example, in jumping down from a height the kinetic energy at impact has to be converted mainly into elastic energy in the muscles, tendons and ligaments. This is accomplished by stretching them. On the other hand, even if the kinetic energy at impact is not too great to be absorbed by muscle action, if the muscles are not sufficiently tensed prior to impact, they will not be able to deal with the shock of landing and balance may be lost or even bones broken (Lee, 1992).

Thus, in the present experiment it was hypothesized that the child prospectively controls her rotation movements towards the extreme pro/supination positions. A more specific question was, how is angular braking regulated given the fact that in the abstract and concrete rotating task the degree of perceptual information supporting the pro/supination movements is different. Prospective control of such perceptuo-motor tasks might seem to require complex neural computation, in this case based on registering the rotating arm's angular position, velocity, acceleration, rate of change of acceleration and so on. The theory described earlier, however, indicates a simpler procedure for controlling the approach towards the maximum pro/supination position: gear the pro/supination movements of the arm so that $\tau'(\alpha)$ remains constant at value k, which would result in $\tau(\alpha)$ decreasing linearly to zero over time. This in turn would mean that α reached zero at contact with the extreme pro/supination position.

It should be noted that because of the varying degree of informational support from the environment that k will be different in the two rotation tasks. However, because k will in both rotation tasks be between 0.5 and 1.0 a *controlled-collision* procedure (with the extreme pro/supination position) is necessary. Following this procedure requires registering $\tau(\alpha)$ and its rate of change. If the child follows the above procedure in controlling the angular braking towards the extreme pro/ supination position, then (1) angular-tau should decrease linearly to zero at contact, and (2) the slope of this linear relationship should lie between 0.5 and 1.0.

Angular-tau was computed on each Selsopot frame as the ratio of angle of the drumstick to the maximum supination/pronation position to the rate of change of the angle. The angle time series during deceleration (determined from velocity profiles: Tpeak velocity→Tmovement ends) where used in these analyses (see Fig. 1). The angle time series α were smoothed with a second order recursive Butterworth filter (cut-off 8Hz), differentiated to give α' and $\tau(\alpha)$ (= 'α'/α') were calculated ('α' = α_{max} - α; α_{max} was used from each trial separately). To test the experimental hypothesis, for each pronation and supination movement the $\tau(\alpha)$ data series was plotted against the time-to-extreme pro/supination position data series.

Test of constant $\tau(\alpha)$ hypothesis

The hypothesis predicts that, during final approach, angular-tau will decrease linearly to zero at contact with the extreme pro/supination position at a rate between 0.5 and 1.0. Thus the plots of $\tau(\alpha)$ against time-to-extreme pro/supination position should be linear.

Fig. 5 presents the plots of $\tau(\alpha)$ against time-to-extreme pro/supination position for movements in the abstract and concrete rotation task, together with the means and standard deviations of the linear regression coefficients, for the child's affected/ non-affected hand.

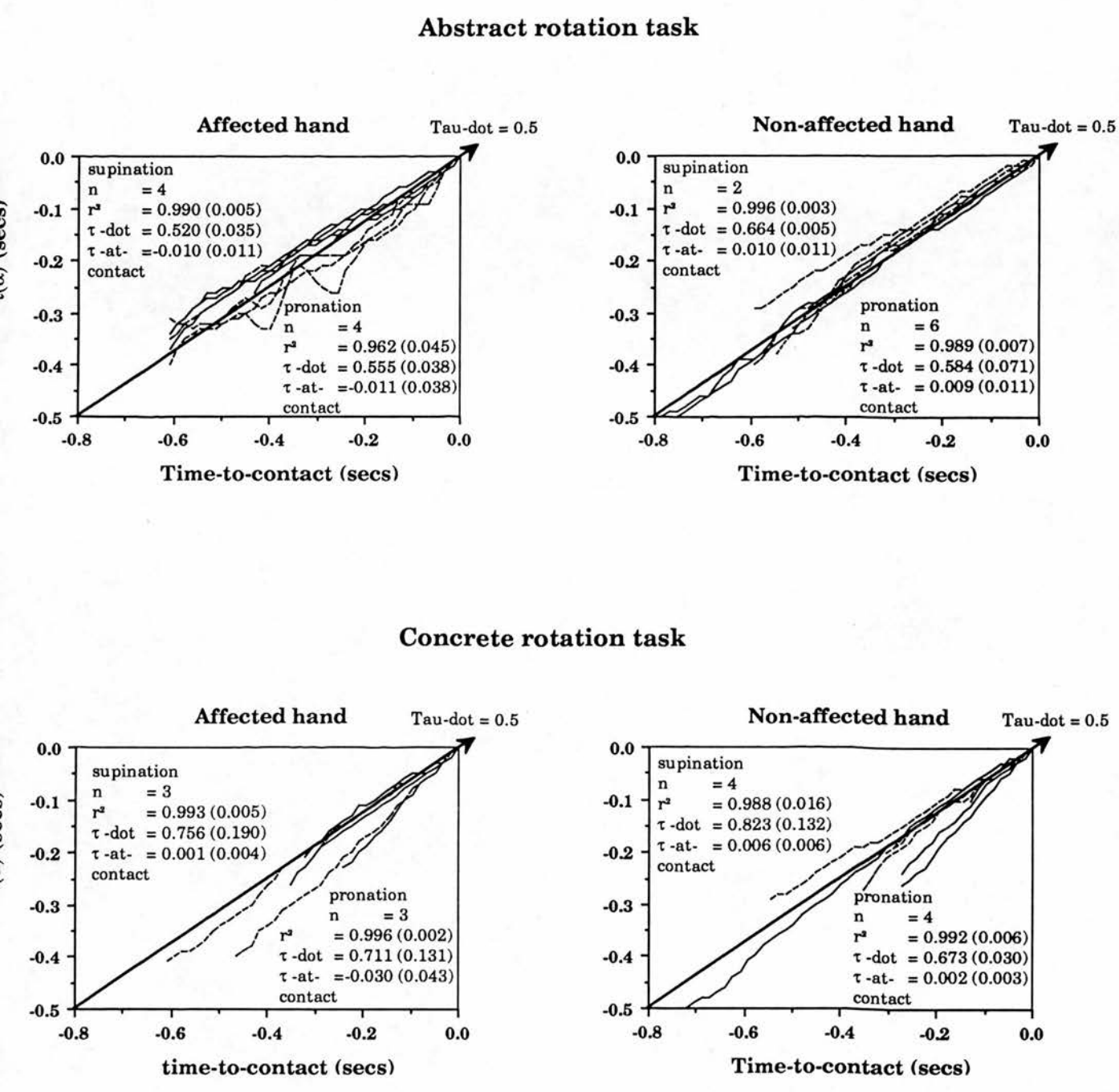

Figure 5a-d. Showing that the child, with both hands, kept tau-dot closely constant during deceleration to contact with extreme pro / supination position. Solid lines: plots for supination movements, dotted lines: plots for pronation movements. Means (standard deviations) of linear regression coefficients of $\tau(\alpha)$ are given in each panel. r^2 values approaching unity indicate linearity - i.e., that the rate of change of $\tau(\alpha)$ was kept constant during deceleration, as predicted. Regression slopes (tau-dot) were always higher in the concrete than in the abstract rotation task, indicating different types of perceptuo-motor control.

In general, pronation and supination movements were controlled similarly. For pronation, the mean (sd) values of r^2 were 0.962 (0.045) for the affected hand and 0.989 (0.007) for the non-affected hand in the abstract rotation task and 0.996 (0.002) for the affected and 0.992 (0.006) for the non-affected hand in the concrete rotation task. For supination, these values were 0.990 (0.005) for the affected hand and 0.996 (0.003) for the non-affected hand in the abstract rotation task and 0.993 (0.005) for the affected and 0.988 (0.016) for the non-affected hand in the concrete rotation task (Fig. 6a-d). These means are very close to a value of 1.0 representing perfect linearity. The data therefore strongly support the constant $\tau'(\alpha)$ hypothesis.

The mean values of $\tau'(\alpha)$ (the regression slopes) were for pronation, 0.555 (0.038) for the affected hand and 0.584 (0.071) for the non-affected hand in the abstract rotation task and 0.711 (0.131) for the affected and 0.673 (0.030) for the non-affected hand in the concrete rotation task. For supination, these values were 0.520 (0.035) for the affected hand and 0.664 (0.005) for the non-affected hand in the abstract rotation task and 0.756 (0.190) for the affected and 0.823 (0.132) for the non-affected hand in the concrete rotation task (Fig. 6a-d).

All mean values are significantly less than 1.0 (For pronation: $p < .0001$, affected hand; $p < .0001$, non-affected hand in the abstract rotation condition and $p < .05$, affected hand; $p < .0001$, non-affected hand in the concrete rotation condition. For supination: $p < .0001$, affected hand; $p < .005$, non-affected hand in the abstract rotation condition and $p < .05$, affected hand hand; $p < .05$, non-affected hand in the concrete rotation condition, t-tests), meaning that angular velocity was not constant, but was decelerating.

These values are also greater than 0.5 (For pronation: $p < .05$, affected hand; $p < .05$, non-affected hand in the abstract rotation condition and $p < .05$, affected hand; $p < .001$, non-affected hand in the concrete rotation condition. For supination: $p < .05$, affected hand; $p < .01$, non-affected hand in the abstract rotation condition and $p < .05$, affected hand hand; $p < .01$, non-affected hand in the concrete rotation condition,

t-tests). This means that the child was decelerating towards the extreme pro/supination position on a *controlled-collision* course (see Fig. 1, Chapter 3)).

In addition, an ANOVA (Task x Hand x pro/supination Movement) was carried out on the linear regression slopes. This analysis showed a significant main effect of Task ($F(1,3) = 10.96, p < 0.05$). Observation of the individual means revealed that the linear regression slopes in the concrete rotation task were significantly higher than those in the abstract rotation task, which indicates that the pronation and supination movements in both tasks were controlled differently. In the abstract rotation task, the regression slopes had a mean value of 0.591 indicating that deceleration towards the extreme pro/supination position was regulated so that it was almost constant but nevertheless collided with the extreme pro/supination position. In the concrete rotation task, however, the mean value of the regression slope was significantly higher, namely 0.717. This meant that the child, appropriately enough, "banged" the drum rather than stopping at it.

4.4 Summary & Discussion

The results of this study show that all three kinematic variables considered in these analyses to capture pronation and supination movements in the forearm were different between the abstract and concrete rotation task.

Analyses of velocity profiles showed that in the concrete task the acceleration phase was longer than in the abstract task. This was caused by the difference in tasks. Namely, in the concrete task the presence of the drum guided the children's hitting actions. This determined the asymmetrical velocity distribution across the pro/supination movements. In the abstract rotation task, however, no such guiding took place and peak velocity was reached sooner. It was reached in the middle of the movement with almost equal duration of acceleration and deceleration phases.

Observation of the phase plane trajectories indicated that especially supination movements in the abstract rotation task reached greater range of velocity. However, range of pro/supination movements was larger in the concrete rotation task. These differences partly replicated the results of the velocity profile analyses: supination movements in the abstract task reached a higher peak velocity with equal length of acceleration and deceleration phases resulting in a circular shape. In the concrete task, range of velocity was smaller and movement amplitude was greater resulting in a more oval shape (see also Chapter 2). Also, from the positions (x-axis) where velocity (y-axis) started decreasing we can see that in the concrete rotation task the start of deceleration of the drumstick was closely timed in relation to the position of the drum. In the abstract rotation task, however, start of deceleration of the drumstick was timed in relation to its vertical position.

Finally, analyses of angular-tau indicated that the child, in both rotation tasks, used a *controlled-collision* procedure. Angular-tau decreased linearly to zero towards contact with the extreme pro/supinaton position at a rate between 0.5 and 1.0. However, angular-tau dot, the mean of slopes of the linear regression lines, was significantly higher for the pro/supination movements in the concrete rotation task.

Thus, although the form of the pronation and supination movements in the abstract and concrete rotation task looked indistinguisable by eye, the underlying movement kinematics proved radically different. How can these differences be explained and what are the implications?

One explanation is that in the abstract rotation task the form and the extent of the rotation movements could not be judged properly because of proprioceptive deficiencies in the arm of the CP child (see Chapter 2). In the concrete task, on the other hand, clear feedback of movement control was provided by the presence of the drum. Another explanation would be that the child understood better what was required of her when she was asked to bang-the-drums or that she was simply more

motivated to perform the rotation movements in the concrete rotation task. A third, perhaps related, explanation is that the quality of informational support from the environment was different between the two rotation tasks. Concrete tasks generally have greater informational support from the environment. In the concrete bang-the-drum task movements could be controlled by visual, auditory and tactile information about the child's relation to the drum, and the attainment of the goal was readily perceptible by the child. If indeed the amount of perceptual information in a perceptuo-motor task influences movement control than these findings could have important consequences for perceptuo-motor learning.

For instance, when learning to play a musical instrument a common practice strategy is to play musical passages slowly for accuracy and then work up the tempo. But, the movements needed to play the passage quickly may not be the same as those practised slowly. Thus, an important question is just how much can you simplify a movement in perceptuo-motor learning without falling into a new, and entirely different, movement pattern which generates its own specific movement kinematics?

Perceptuo-motor skills are performed in relation to their unique set of perceptual circumstances and require, therefore, a unique coordinative solution to a perceptuo-motor problem. This suggests that coordinative solutions are subordinate to perceptual circumstances and that movement patterns can only be regarded as emergent properties of the actor's exploitation of the various sources of perceptual information to meet the requirements of a task (Bootsma, 1988; Fowler & Turvey, 1978; Saltzman & Kelso, 1987).

This has important consequences for devising intervention programmes for children suffering from brain damage. Namely, this would entail that therapies for overcoming motor disorder should not only concentrate on promoting movement patterns which may or may not transfer to perceptuo-motor activities of daily life, but should also concentrate on these activities directly. In other words, for perceptuo-motor

learning to take place, all sources of perceptual information relevant to the performance of the task should be present during the acquisition process.

Not possible; if performance is 'unnatural or inept'.
c.f. Limiting deg. of freedom.

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Chapter 5

Timing (Body) Characteristics in Cerebral Palsy

(Paper presented at the Second European Conference on Ecological Psychology (June, 1992), Strathclyde University, Glasgow (U.K.).)

Abstract *Interceptive timing actions of Cerebral Palsied (CP) children and normal nursery children were analysed to determine what source of perceptual information these children used to initiate their hands to strike an approaching ball. The results suggested that both groups of children used the optic variable tau for initiating and guiding the striking actions. The affected hands of the CP children always initiated the striking actions at an significant larger value of tau which supports the hypothesis that the optic variables specifying the tau-margin contain important body/action scaled information.*

5.1 Introduction

The foundation of vision for all animals is the optic flow field (Gibson, 1966), the changing pattern of light reflected from the environment to a moving eye. A flow property of wide application for action is the *tau* margin (Lee, 1976, 1980). The optical variable tau specifies a particular time relation between an observer and an approaching object, namely the distance between observer and object divided by the relative rate of approach. The tau-margin equals time-to-contact under constant velocity. However, interceptive actions frequently have to be timed under conditions

where approach velocity is not constant, like in catching something falling. If the approach is accelerative, as under gravity, then, strictly speaking, the tau-margin to the approach surface is an overestimate of the time-to-contact with the surface. However, with normal accelerations the overestimate is negligibly small over about the last 300 ms of approach (Lee *et al.*, 1983).

Experiments indicate that the tau-margin is indeed used in timing actions under both constant velocity and accelerative approaches (Lee & Reddish, 1981; Wagner, 1982; Warren *et al.*, 1986; Sidaway *et al.*, 1989; Lee *et al.*, 1983; Bootsma, 1989; Savelsbergh *et al.*, 1991). These studies show that it is not, in principle, necessary to pick up information about distance or speed in order to register the tau-margin, since it is directly specified in the optic flow field as the inverse of the relative rate of dilation of the closed optical contour generated by an approaching object or surface.

However, in practical situations, when information about distance and velocity is presumably available, might not time-to-contact be computed from distance and velocity? It is hard to see what would be the advantage of such a computational method. In the first place, computing the tau-margin from distance and velocity, however they were perceived, would introduce two sources of error and these would compound to give greater error in the estimate of the tau-margin (Lee & Young, 1985). Secondly, information about distance and velocity has to be scaled in terms of body/action dimensions, and it turns out that this requires registering the tau-margin (or its equivalent) from the optic flow field.

Consider striking and approaching ball with the hand. In a certain sense, information about the ball's current position, velocity and acceleration is needed, but it is not information about its approach in centimetres and seconds or any other arbitrary unit of measure. What is required is information specifying the specific time relation between the (moving) hand and the approaching ball. In general, things need to be perceived in terms of the type and magnitude of action that could or is to be applied to them: i.e., the *affordances* of things are what need to be perceived (Gibson, 1979).

The concept of affordances has provided a framework for a body of experimental work that corroborate the thesis that objects and surfaces in the environment are scaled in terms of body/action dimensions. For example, it is now known that people can accurately perceive the ideal riser height for comfortable stair climbing (Warren & Whang, 1987), and the size of door that they could pass through in comfort (Warren, 1984). Also, visual regulation of gait to hit the take-off board in the long jump run-up (Lee *et al.*, 1982) and when running over irregularly spaced stepping stones (Warren *et al.*, 1986), are nice examples of the use of body/action scaled perceptual information. The long jumper and the runner adjust cycle time, by regulating the vertical impulse applied to the ground, in order to control where the foot strikes the ground. Especially in the latter two cases, the optic information is solely about the tau-margin. The optic variables specifying the tau-margin must therefore contain important body/action scaled information about distance, size and velocity as well as about time.

This hypothesis was tested further in the following study. It was investigated whether or not cerebral palsied (CP) children scale perceptual information in terms of their bodily characteristics and action capabilities. Especially asymmetric handicaps, e.g. stroke and hemiparetic cerebral palsy, in which one side of the body is more affected than the other, can give us a special insight into the role of body/ action scaled perceptual information. A group of hemiparetic CP children was tested striking a moving ball. Their timing behaviour was compared with that of a control group. It was expected that because of their asymmetric handicap the cerebral palsied children would show a difference in timing behaviour between the two hands, whereas the control children would show no such difference.

First, it was examined what underlying principle governs initiation of the striking actions. The governing principle was then analysed further as to how it varied between the affected hand and non-affected hand of the CP children. Second, it was investigated what happened when body/action scaled perceptual information was removed from the timing task.

5.2 Method

Subjects

A consultant at the local children's hospital referred six children with congenital CP, diagnosed as hemiparetic, who were all of normal intelligence and ranged in age from 4 to 8 years (Mean 5 years 11 months; SD 18 months) to serve as subjects. The right side of the body was affected in three boys and one girl. The left side was affected in two boys. Using Ingram's (1984) classification, one of the children was severely affected, rendering one hand almost functionless, four were moderately affected and one mildly so. Six normal children served as age-matched controls, ranging from 3 years 10 months to 8 years 11 months (Mean 5 years 8 months; SD 30 months). Three boys and one girl attended the departmental nursery school and one boy and one girl a normal primary school. Four children in the control group were right-handed and two left-handed as assessed by a separate study (Mathieson, 1992).

Apparatus

To measure the subject's timing performance a ball-strike apparatus was designed (see Fig. 1). A rubber ball (diameter 15 cm) was released from the top end of a track consisting of two aluminium rods (200 cm x 1.5 cm; 7.5 cm apart) which ended level with the subject's edge of the table (78 cm high) and began 6 cm, 17 cm, and 28 cm above that height for velocities 1, 2, and 3 respectively. This resulted in an end to end ball movement time of 3.97 secs for velocity 1, 2.54 secs for velocity 2, and 2.09 secs for velocity 3. At the subject's end of the track two bats (31 cm x 23 cm x 1 cm), one for the left and one for the right hand, were mounted on a separate part of the apparatus. This part was placed over the track and could slide independently backwards and forwards to adjust for different arm lengths.

The two bats could also be swung by pressing a button mounted on a backboard (5 x 5 cm) attached to velcro and fastened to the arm of the chair in which the subjects sat. Brass rods were mounted in plunger housings to either side of the bats in such a way that the rod was just touching the bat. When the subjects pressed the button a switch/solenoid system activated the brass rods which then emerged two centimetres and struck the bats. The force applied by the solenoid system was enough to strike the approaching ball off the track.

Figure 1. Nursery school child taking part in the experiment.

An infrared light emitting diode was fixed to each of the subject's wrists, and bats making four LED's in all. These were viewed from above by a Selspot camera at 2.5m distance. The optical axis of the camera was vertical. The Selspot data were recorded on a computer at 62 frames per second. Each session was also videotaped, using a video camera facing the subject.

Procedure

The children sat on a chair close to the table with the track directly in front of them. Their arms rested on the arms of the chair. Each child performed the timing task under two different conditions, namely (1) striking the bat with the hand and (2) pushing a button to strike a bat. Each condition was performed both with the left and with the right hand separately. In each trial the ball was rolled down the track towards the child at varying speeds. In condition (1), the children were instructed to strike the bat with the hand in one smooth movement so that the bat struck the ball as it passed. In condition (2), the children were instructed to press a button with a minimum of finger movement to activate lateral movement of the bat in time to strike the moving ball off the track. The experiment comprised three separate sessions each lasting about 25 minutes. An individual session consisted of the two experimental conditions at three different speeds, in random order. At each speed, six trials for the left hand and six trials for the right hand in both the hand strike and button press task were recorded, resulting in a total of 72 trials per child.

Measures

Selspot measures

From the Selspot records the following times were recorded (see Fig. 2).

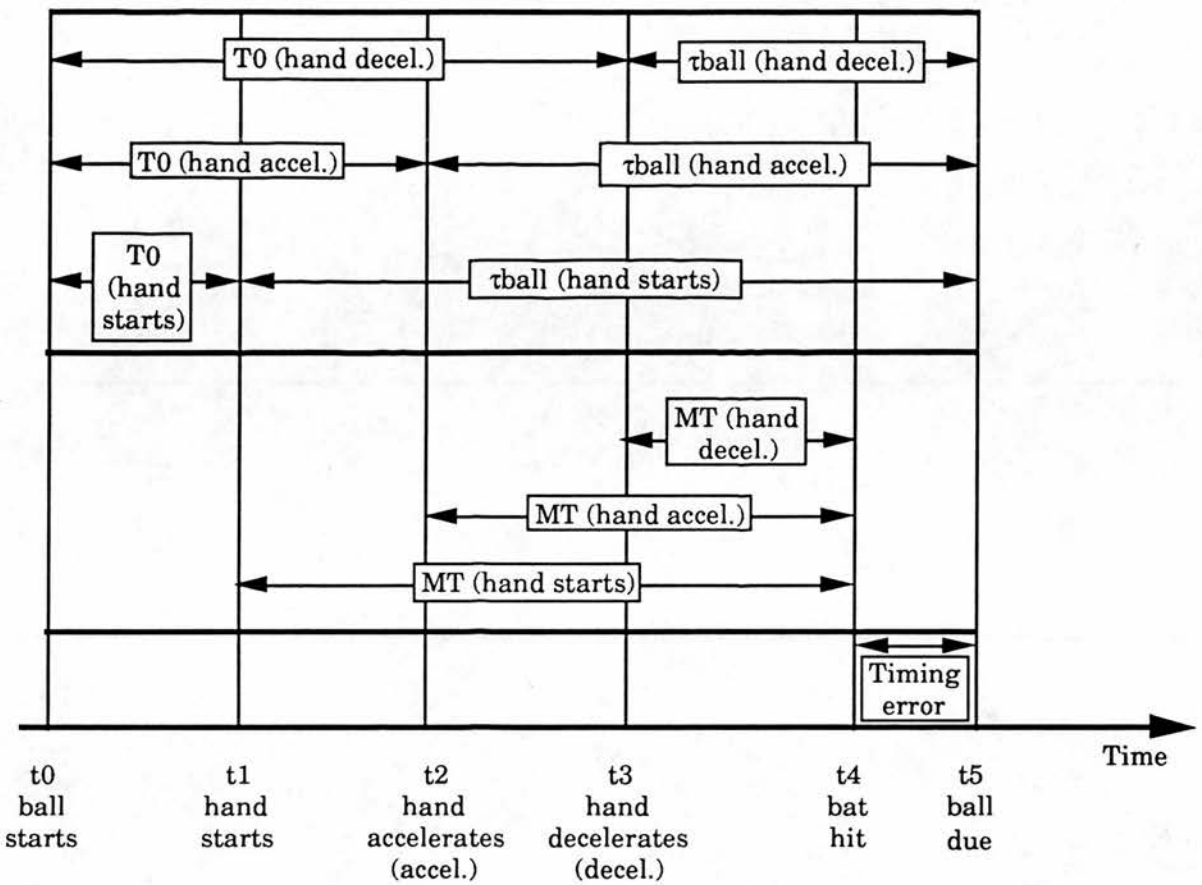


Figure 2. Schematic represention of the six different times (t0-t5) measured from the Selspot records. From these basic times the Initiation Time (with respect to both the start and arrival of the ball), the Movement Time, and the Timing Error were computed for each striking movement.

(t0) Ball released by the experimenter.

(t1) Hand started the striking movement, indicated by a change in the X-coordinate of the wrist LED.

(t2) Hand started accelerating, indicated by systematic increase in the y-component of the velocity of the wrist LED leading up to the strike.

(t3) Striking movement of hand started decelerating, indicated by start of systematic decrease in the y-component of the velocity of the wrist LED.

(t4) Bat moved in X-direction, indicated by the first change in the x-coordinate of the bat LED.

(t5) Ball due at striking place, computed from ball release time and calibration of ball movement (see below).

Video measures

To measure the consecutive positions of the ball during its approach to the striking point a separate video analysis was carried out. For each of the three ball speeds ten trials of the ball rolling down the slope were recorded from the side. These recordings were made with a Panasonic F10-CCD video camera and played back on a large Sony PVM-201CE monitor screen. At a rate of 50 frames per second (every 20 msec.) the x-coordinates of the centre of the ball were digitized, frame by frame, using a Panasonic NV-D80 HQ, (digital still & digital double fine slow) video recorder and an Archimedes 440/1 computer & mouse. The position data were then smoothed using a second order recursive Butterworth filter with a cut-off frequency of 8.0 Hz.

The smoothed position data of each of the ten trials, at the three different ball speeds, were then plotted against time at 0.02 secs steps and fitted with the best possible regression line. This meant a second order polynomial regression line (mean R^2=0.999 across velocity/trials). The equations of these regression lines were then used to determine the position, the velocity and the rate of change of velocity of the ball during its approach.

5.3 Results

Governing variable of initiation

What governed when the children started to (a) move the hand (HS), (b) accelerate it (HA) and (c) decelerate it (HD). Five possible governing variables were considered for these initiation points.

T0: Initiation point occurs a certain time after ball is released (at time T0).
This would be a simple initiation variable for the children to use. Namely, the children would initiate the striking actions a certain time interval after the ball was released by the experimenter.

Tball: Initiation point occurs a certain time before ball due to arrive at striking place.
The best initiation variable for the children to use would be a certain time interval-before-arrival at the striking place. This variable would predict the time it took for the ball to arrive at the striking point. However, this would entail complex computations involving estimates of acceleration.

Zball: Initiation point occurs when ball is certain distance from the striking place.
A third possible initiation variable for the children to use would be a certain position of the ball on the track. In this case the striking actions would be initiated earlier if the ball speed is higher.

Vball: Initiation point occurs when ball reaches certain velocity V.
Using Vball as an initiation variable the children would start their striking actions on the basis of the ball reaching a certain critical velocity. In this case, the striking actions would be initiated earlier if the initial velocity of the ball was higher.

τball: Initiation point occurs when τball (= Zball / Vball) reaches certain value.
The simplest and most direct initiation variable would be to start the striking actions at a certain value of τball. This variable provides under normal accelerative approaches an accurate enough estimation of the time it will take the ball to reach the striking place, without the need of complex computations involving distance, speed and acceleration.

To investigate which of these initiation variables governed the initiation points, the mean standard deviations of T0, Tball, Zball, Vball and τball were compared across the three different ball speeds (see Fig. 3). However, the standard deviations of the five governing principles are in different units. This means that a straight comparison betweeen standard deviations is not possible because by simply changing the units (e.g. from centimetres to metres) it is possible to change the value of the standard deviation. Therefore, to make a full comparison between these governing principles possible, the mean standard deviations were devided by their means to obtain a proportional value: the index of dispersion.

The individual values for T0 and Tball at HS, HA & HD were taken from the Selspot records. The values for Zball, Vball and τ ball were obtained by substituting the time points HS, HA & HD into the regression equations derived from the video analysis. Thus, every value of Zball, Vball and τ ball was in fact a mean value calculated across 10 trials/speed. Means and standard deviations of those (mean) values were calculated at each initiation point, with each hand, across ball speed (over 18 values).

When comparing units such as T0, Tball, Zball and Vball with a ratio like τ ball in terms of their standard deviations, it is important to realise that the component of variation introduced by measurements in the analysing process particularly affects a ratio. In particular, the separate components of variation in measurements of Zball and VBall are represented combined in τ ball. Therefore, the component of variation due to measurement error is likely to be higher in the ratio τ ball than in Zball and Vball separately. To compensate for this cumulative effect, the total amount of variance (across 18 trials) was corrected for the amount of variance introduced by the measurements.

T0 and T5 were corrected for the amount of variance due to measuring the time it took the ball to reach the striking place. Ten trials at each ball speed were recorded with Selspot. The variability of these measurements was subtracted from the total amount of variance. Zball, Vball and τ ball were corrected for the amount of error introduced by the video digitizing process. The variability resulting from substituting initiation points HS, HA and HD into the ten regression lines per speed was subtracted from the total amount of variance. The new, true values of the mean standard deviations were then devided by their means in order to the create the indices of dispersion. The results of these combined Selspot and video analyses are presented in Figure 3a-f.

To test wich variable governed the children's initiation point, a three-way repeated measures ANOVA (Group x Hands x governing Variable) was carried out on the indices of dispersion at each of the three initiation points HS, HA & HD separately. These analyses revealed highly significant main effects of Variable, HS: ($F(4,40) = 22.99, p < .0001$), HA: ($F(4,40) = 77.43, p < .0001$) & HD: ($F(4,40) = 109.45, p < .0001$). To further investigate which of the initiation variables had the smallest index of dispersion and whether they were significantly different from each other further tests were carried out (see Table 1).

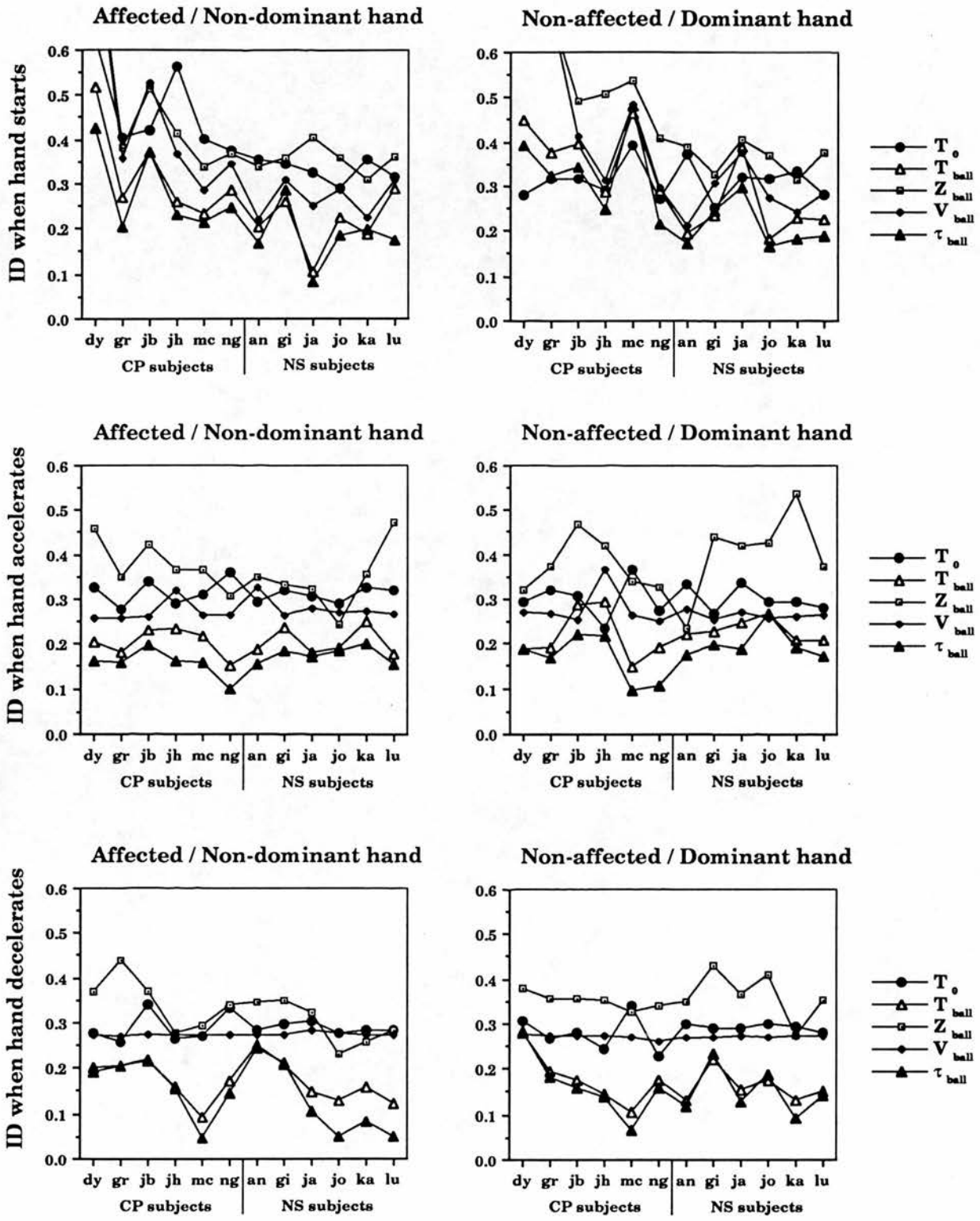


Figure 3a-f. In each graph, the indices of dispersion of the five initiation variables are plotted for the two groups and for each child separately. Between graphs, the affected / non-dominant hand is compared with the non-affected / dominant hand at each of the three initiation points HS, HA and HD.

Initiation point	Governing variable	Mean ID	Newman-Keuls				
			T0	Tball	Zball	Vball	τball
Hand starts	**T0**	0.356	x	<.05	<.01	n.s	<.01
	Tball	0.288		x	<.01	<.01	<.05
	Zball	0.447			x	<.01	<.01
	Vball	0.376				x	<.01
	τball	0.240					x
Hand accel.	**T0**	0.307	x	<.01	<.01	<.01	<.01
	Tball	0.214		x	<.01	<.01	<.01
	Zball	0.376			x	<.01	<.01
	Vball	0.273				x	<.01
	τball	0.174					x
Hand decel.	**T0**	0.287	x	<.01	<.01	n.s	<.01
	Tball	0.170		x	<.01	<.01	<.05
	Zball	0.340			x	<.01	<.01
	Vball	0.273				x	<.01
	τball	0.146					x

Table 1. Mean indices of dispersion and significance levels of Newman-Keuls tests between initiation variables at each of the three initition points HS, HA, HD.

From the mean ID in Table 1 it can be seen that, in general, the indices of dispersion of τball were smaller than those of T0, Tball, Zball & Vball. Thus, more specifically, at initiation points HS, HA & HD the indices of dispersion of τball were smallest for the CP children's affected and non-affected hand and for the nursery children's non-dominant and dominant hand. Thus, these results suggest that τball was the governing variable for initiating the striking actions.

This result was to be expected because initiation variables T0, Zball and Vball are all rather unsophisticated. Namely, T0 and Zball predict that, if movement time remains constant, the children will strike the bat earlier if the ball's speed is lower and Vball predicts that on lower ball speeds the children will strike the bat later. All three strategies would therefore result in rather large timing errors.

Using strategy Tball would be the best strategy possible for the children to use, since this strategy predicts the real time it takes the ball to reach the striking place, under both constant velocity and constant accelerative/decelerative approaches. However, such a strategy would involve a complex predictive system that takes into account any available information about the ball's current position, velocity, acceleration, rate of change of acceleration, rate of rate of change of acceleration, and so on. Lee and Young (1985) have argued that such an over-complex system could entail unnecessary delays in making use of the information as well as oversensitivity to noise, and as such would be unlikely to have evolved. A better system, in their view, is robust rather than over-refined and takes advantage of the most reliable and rapidly available information. The robust system proposed by Lee (1976, 1980) is one that perceives time-to-contact-at-constant-velocity, defined as distance away devided by speed of approach.

The results of the present experiment suggest that the children's striking actions were indeed geared to τball as against being geared to Tball. Although the ball was travelling under constant accelerative approaches, it appeared that the children used the τball variable as the governing variable for striking the ball with the bat at the right moment. Therefore, only means and standard deviations of τball will be used in further analyses.

How is τball used?

Having established that the CP children and the nursery children used the τball variable as the governing variable when initiating the striking actions with both the affected/non-dominant hand and non-affected/dominant hand, it was then investigated whether there were any differences in the use of τball between groups of children and hands used. Means and standard deviations of τball at initiation points HS, HA, HD and at the time when the bat was struck (BS) are plotted in Figure 4.

Mean (τball)

The cerebral palsied children initiated the striking actions much earlier with the affected hand than with the non-affected hand. Their affected hand started (HS) the striking actions always at a larger τball value than the non-affected hand did. Between the nursery children's non-dominant hand and dominant hand no such differences were found. This is shown in a mixed measures ANOVA (Group x Hand x Initiation point) by a significant three way interaction, $F(2,20) = 13.68$, $p < .0002$.

Sd (τball)

A similar three-way interaction effect (Group x Hand x Initiation point) was also found for the sd(τball), ($F(2,20) = 6.50$, $p < .01$). This could indicate that the affected hand in the CP group was more variable than the non-affected hand when starting (HS) the striking actions. However, performing the same ANOVA on the indices of dispersion of τball (sd(τball)/mean(τball)) did not reproduce the same three way interaction effect. Therefore, the fact that sd (τball) was higher for the affected hand than for the non-affected hand in the CP group was probably caused by the higher values of mean (τball).

Also, the values of sd(τball) at HA & HD for the CP children's affected hand was the same as for the the non-affected hand. A further significant main effect of Group

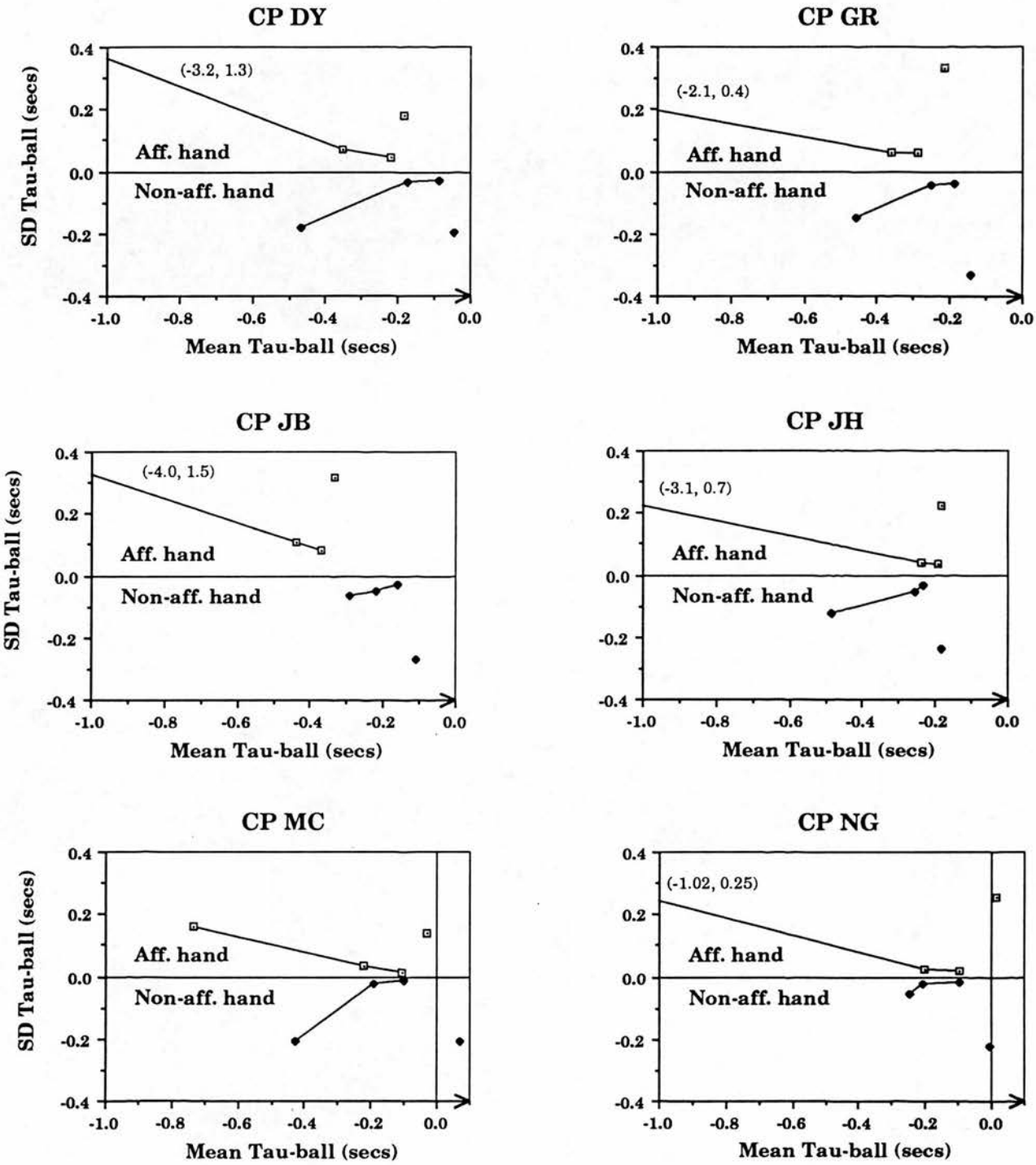
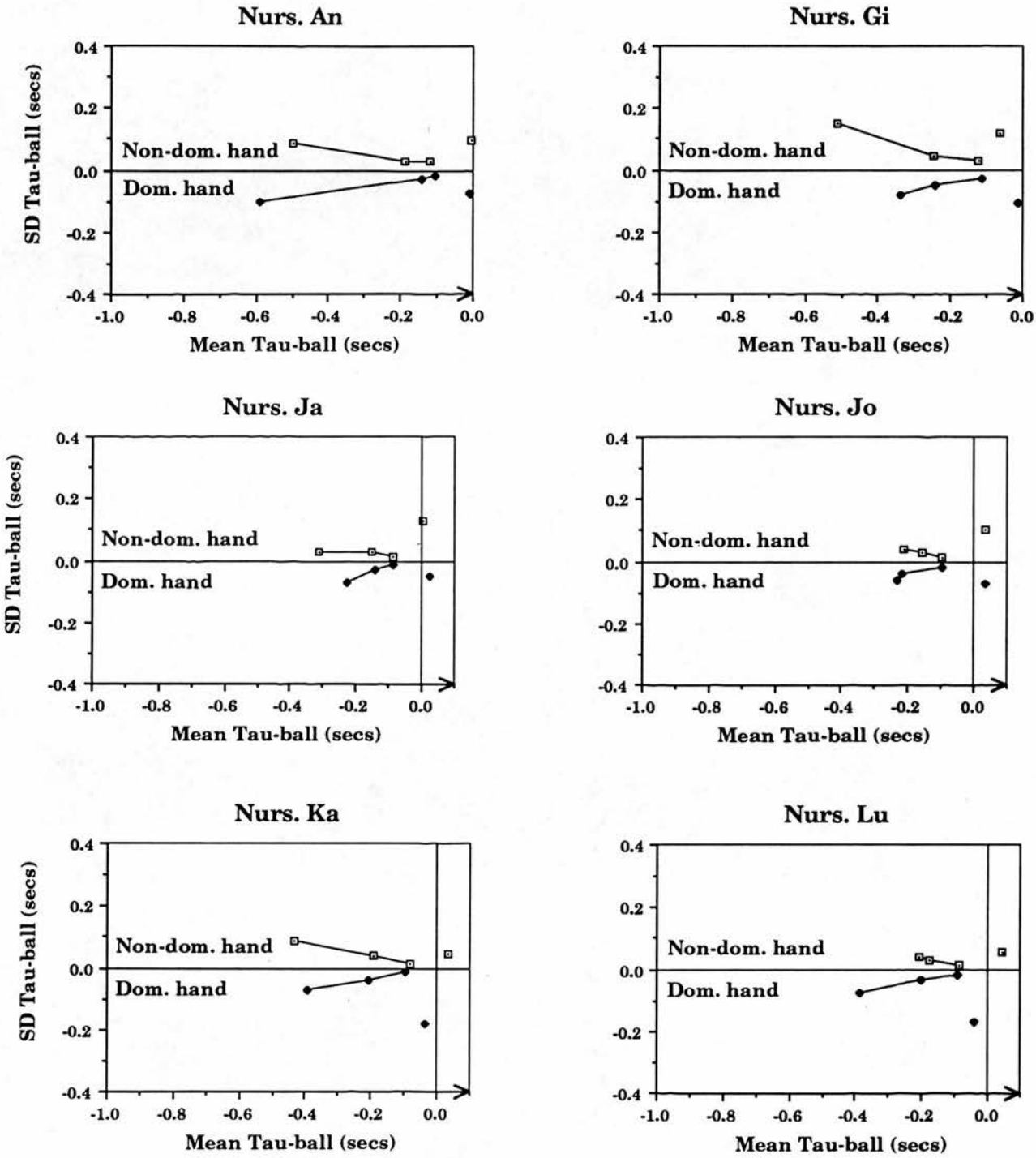


Figure 4. Standard deviations of tball plotted against mean values at (reading from left to right) the three initiation points HS, HA, HD and at the moment the bat was struck (BS) for the affected / non-dominant hand (top half of graphs) and the non-affected / dominant hand (bottom half of graphs).



(Caption Figure 4 continued) Note that standard deviations of the non-affected hands and dominant hands are plotted with negative values. This is done for display purposes only. Also, values are given in brackets (x,y) for large coordinates.

showed that the CP children were, in general, across initiation points, more variable in initiating the striking actions than the nursery children, $F(1,10) = 9.10$, $p < .05$.

Furthermore, a significant main effect of Initiation point was also found, $F(2,20) = 15.90$, $p < .0001$. This shows that, for both the affected and non-affected hand in the CP group and for both the non-dominant hand and dominant hand in the nursery group, the variability of τball at HS was larger than at HA, which was also larger than at HD.

The decreasing trend in standard deviation of τball indicates a zeroing-in of the subsequent initiation actions towards the arrival of the ball at the striking place. This indicates that the whole act of striking the ball with the bat at the right moment was under continual visual guidance, that the hand was kept geared to a value of τball. If the striking activities were performed as a pre-programmed, practised package or, in other words, as a ballistic act, the standard deviations towards the end of the striking action would only have increased rather than decreased because of the additional variation of the children's movement time.

This is probably what happened at the very end of the striking actions when the bat was struck. From Figure 4 it can be seen that the standard deviations of the time the bat was struck (BS) increased dramatically for both the CP children and the nursery children. Apparently, the whole act of striking the ball with the bat was under continuous perceptual control except for a ballistic hand swipe at the last moment before contact when the striking actions were performed more or less 'blind'.

How are movement time and τball correlated?

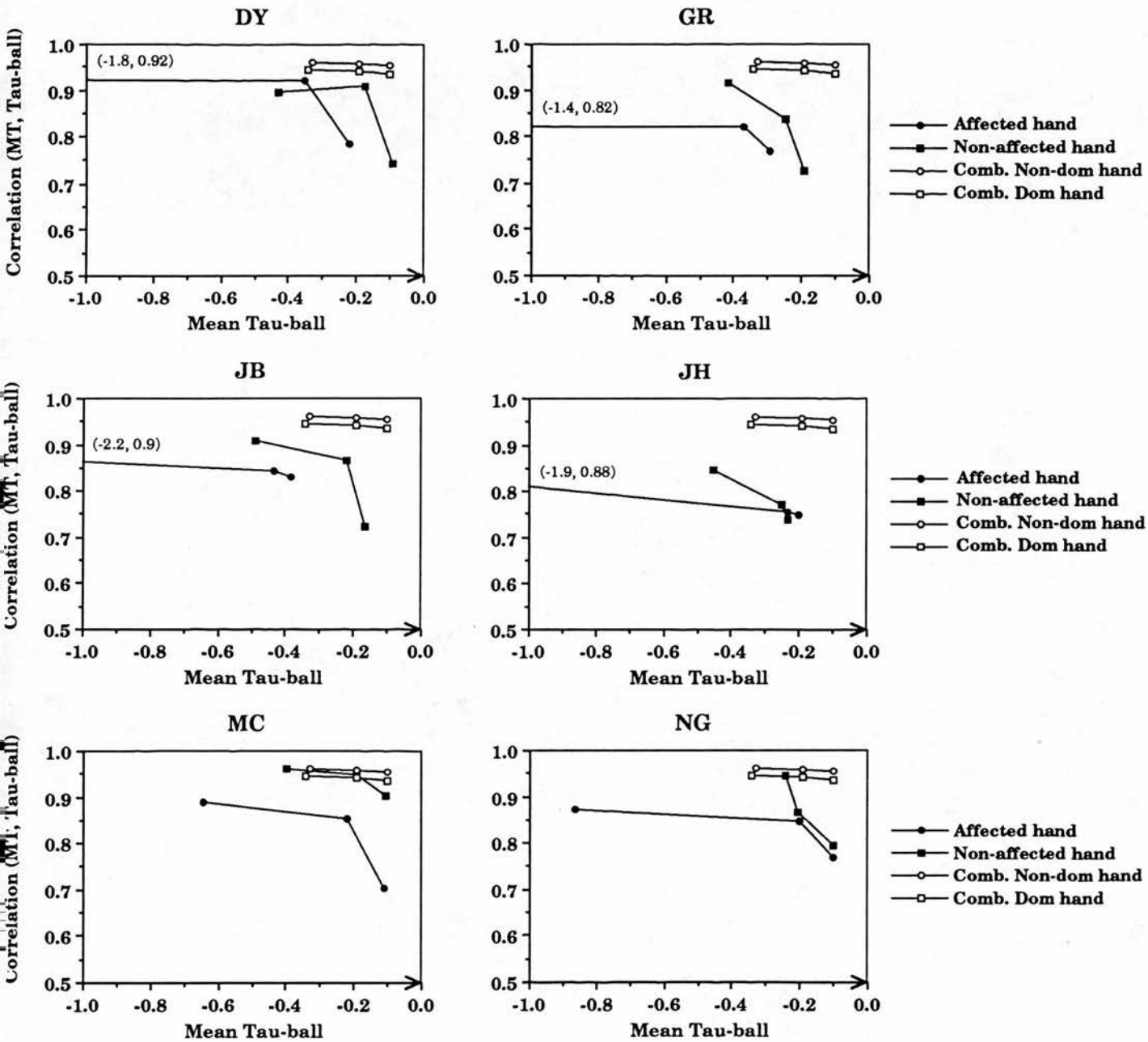
The degree to which the children's striking actions were continuously guided perceptually until the time the bat was struck is also indexed by the correlation between movement time (MT) and mean(τball). A high positive correlation would

indicate that the striking action was being modulated to fit the available time-slot. Figure 5 shows these correlations for each CP child separately in addition to the combined nursery children.

The correlation between movement time and τball across trials was overall high and positive. This means that if the children's preparatory striking actions were initiated earlier (or later) then they make the subsequent movement up to the moment the bat was struck longer (or shorter). The correlation coefficients for the nursery children were slightly higher than those for the CP children $F(1,10) = 59.99$, $p < .0001$), suggesting a tighter coupling between movement time and τball in this group. The ANOVA also showed a significant two-way interaction (Group x Initiation strategy). Further analyses on this two-way interaction showed that the correlation between movement time and τball drops at initiation point HD for the CP group only, indicating less precise regulation of duration of deceleration $F(2,20) = 41.80$, $p < .0001$).

Terminal accuracy

So far, the way in which the children's striking actions were initiated and how these actions were continuously controlled perceptually throughout the striking movements have been investigated. In this section the terminal accuracy will be examined. Means, standard deviations (SD) and root mean squares (RMS) of the children's timing errors for each group of subjects in each condition for both hands are presented in Figure 6.



'igure 5. Correlations of movement time and tball are plotted against the values of mean(tball). In each graph, the values of the affected / on-dominant hand and non-affected / dominant hand at initiation points HS, HA & HD are represented for each CP child separately nd for the nursery children combined.

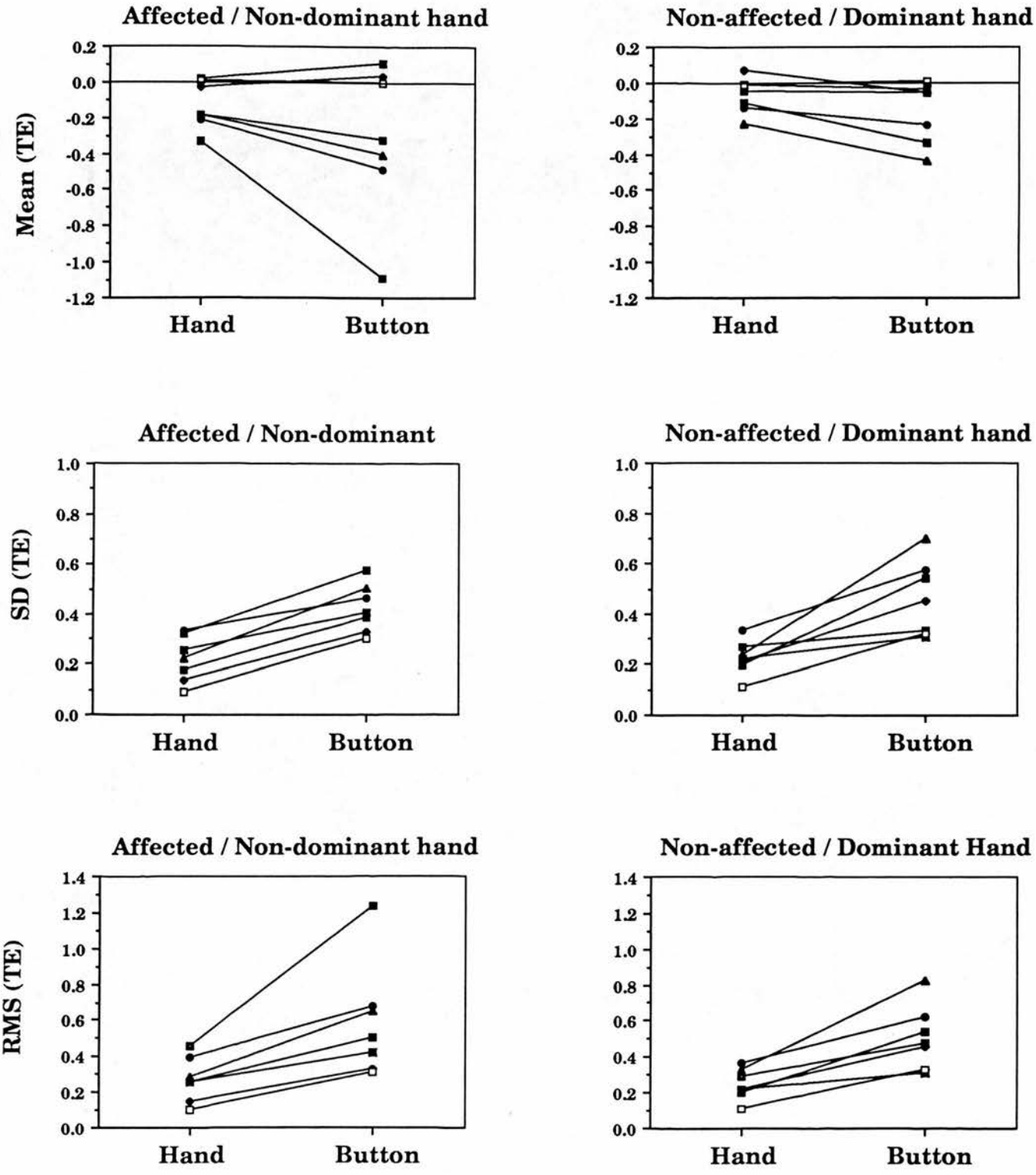


Figure 6a-f. Means, standard deviations and root mean squares of timing errors for both the individual CP children's affected / non-affected hand (closed symbols) and the combined nursery children's (N=6) non-dominant / dominant hand (open symbols) in the hand strike condition and in the button press condition.

Mean TE

Mean timing errors were generally small and early. A mixed measures analysis of variance (Group x Condition x Hand) on the mean timing error showed no significant main effects nor any significant interaction effects. Thus, no differences were found between the affected vs. non-affected hands and non-dominant vs. dominant hands in neither the hand strike or button press condition. There were also no significant differences in mean timing error beween the CP group and the control group.

SD TE

However, the CP children were less consistent in their terminal timing performance. An analysis of variance (Group x Condition x Hand) on the mean standard deviations of timing errors confirmed this with a significant main effect of Group, $F(1,10) = 38.25$, $p < .0001$. A significant main effect of Condition ($F(1,10) = 32.72$, $p < .0002$) revealed that both the CP children and the nursery children were much more variable on the button press condition than on the hand strike condition.

RMS TE

An analysis of variance carried out on the RMS values (Group x Condition x Hand) basically repeated the results found on the standard deviations. Namely, both main effects of Group ($F(1,10) = 30.13$, $p < .0003$) and Condition ($F(1,10) = 58.89$, $p < .0001$) reached significance.

5.4 Summary & Discussion

This study investigated what perceptual information was used by CP children and nursery children when performing on an interceptive timing task. The results suggested that the affected hand and the non-affected hand of the CP children and the non-dominant hand and dominant hand of the nursery children used τball as the governing variable for initiating the hand and that the whole act of striking the ball was under continual visual guidance, that was kept geared to τball until the moment the bat was struck. This means that although the ball was travelling under constant accelerative approaches τball provided an accurate enough estimation of the time it took the ball to reach the striking place, without the need of complex computations involving distance, speed and acceleration.

The results also showed that the CP children initiated the striking actions much earlier with the affected hand than with the non-affected hand, i.e. at a significantly larger mean value of τball. However, it should be noted that although the affected hand started the striking actions significant earlier than the non-affected hand, these preparatory actions were nevertheless part of a highly organised striking action, as was shown in the results.

First, the governing variable for initiating the striking actions was τball. This was also true for the CP children's affected hand. Thus although one of the CP children's hands was affected, it still was governed by τball for initiating the striking actions instead of one of the other, less sophisticated, variables T0, Tball, Zball or Vball.

Second, the indices of dispersion of τball at the three initiation points studied of the CP children's affected hand did not differ significantly from those of the non-affected hand, nor were they different from the nursery children's non-dominant and dominant hands. This indicates that the affected hand was as consistent in initiating the striking actions as the non-affected hand, non-dominant and dominant hand.

Third, for the affected and non-affected hand and for the non-dominant and dominant hand the variability of τball decreased towards the end of the striking actions showing, for *all* hands, a zeroing-in of the subsequent initiation points towards the arrival of the ball at the striking place.

Fourth, the high positive correlations between movement time and τball indicated that the striking action of the CP children's affected hand was modulated to fit the available time slot. In other words, in starting early the affected hand made the subsequent striking movements longer. The correlation coefficients for the nursery children's non-dominant and dominant hand were only slightly higher.

Fifth, mean timing errors were generally small and there were no significant differences found between the CP group and the nursery group nor between hands used. Thus, in starting early the CP children compensated for the relative slowness of the affected arm to hit the approaching ball at the right time.

In sum, the results showed that although the affected hand of the CP children initiated the striking actions earlier than the non-affected hand, the striking actions were nevertheless highly organised and the early initiation actions were an integral part of the striking movement. In the next Chapter (Chapter 6) these striking movements will be examined in even more detail. The way in which the striking actions were controlled towards 'collision' with the bat will be analysed for the affected and the non-affected hands. Based on the results found in the present study it is expected that the striking actions of the affected and non-affected hands will be similar.

So far, it can be concluded that the perceptual information specifying time-to-arrival of the ball with the hitting place was scaled in terms of the handicap of the CP children's affected arm. Similar evidence of the use of body/action scaled

perceptual information in handicapped children have also been found by Forsström and Von Hofsten (1982). Children with mild neurological problems were studied on a task that required interception of a small object on the end of a moving rod. Visual information had to be used to determine object speed and predict an interception point in the organization of a correct reaching movement. All children reached ahead of the moving object, which showed their ability to anticipate an interception point ahead of the moving object. The handicapped children reached further ahead than the normal children and thus were later in their interception of the moving object. The authors analyzed the direction of the initial movement of the arm and found that the handicapped children aimed toward the interception point they subsequently achieved. This suggests that the handicapped children took into account a projected movement delay in intercepting the object, which demonstrates body/action scaling of perceptual information in relation to impaired muscle activation.

The existence of body/action scaled information has also been demonstrated in adult subjects. Hallford (1984) showed that scaled information was used in visual size judgement tasks using a body-referenced standard and an arbitrary standard. Observers were more accurate and had higher confidence when judging whether they could grasp rectangular objects with one hand than when judging their widths relative to a standard object that was first viewed and then held during the judgements. This result indicates the primacy of body-scaled perception. In an independent study of perception and action in stair climbing (Warren, 1984), it was also found that perceivers were highly accurate at judging the dimensions of environmental objects with respect to their own action capabilities. The people perceived "climbability" of a stairway in terms of their leg length. Thus, the observers appeared to make accurate perceptual judgements that were scaled to their own body dimensions. Similar results have also been found in a great number of other studies. See for an overview of these studies Adolph et al. (1992).

The importance of body/action scaled perceptual information for specifying τball was also shown by the fact that in the more abstract 'button-press' condition timing behaviour in both the cerebral palsied children *and* the nursery children was more variable. Thus, removing the body/action scaled perceptual information outweighed the putative advantages of the button in the CP group. Instead of simplifying the task by eliminating the movement component from the timing action (cf. task-complexity hypothesis, Henry & Rogers, 1960), the 'button-press' condition became more difficult because at the same time body/action scaled perceptual information was no longer available.

Similar findings were reported by Bootsma (1989). His subjects were also more variable when carrying out abstract perceptuo-motor actions. In his study, subjects were required (a) to strike a ball with the natural arm and (b) to release an artificial arm (with a button) to strike a ball. Initial accuracy (variability of the initiation time) and terminal accuracy (number of balls struck) were found to be more variable in the artificial arm condition. Bootsma (1989) concluded that the more the required action was separated from a natural perception-action coupling, the less precise the timing response was; this finding is corroborated by the results of McLeod, McLaughlin, and Nimmo-Smith (1986).

In conclusion, we interpret these findings to suggest that the τball 'contained' important information for controlling action. It afforded predictive information for timing interceptive actions and, at the same time, it also provided the observer with a referential starting point for environment perception, because the perceptual information was body/action scaled. In this Chapter we have shown some of the temporal information provided by τball. Tau-dot, the time derivative of tau, affords direct information for controlling speed of approach (see Chapters 3 & 8 (Appendix)), on which an activity such as intercepting an approaching ball also depend. This will be shown in Chapter 6.

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Chapter 6

Controlling Interceptive Actions in Cerebral Palsy

Abstract *The experimental data of the interceptive timing actions of CP children and nursery children, which were collected in the experiments reported in Chapter 5, were analysed in further detail. It was investigated how these children regulated deceleration of the hand during the final approach before contact with a bat. The results showed that both groups of children controlled deceleration of the hand by keeping constant the rate of change of the ratio τ(hand to bat) / τ(ball to bat) at a value between 0.5 and 1.0. The affected hands of the CP children were clearly handicapped in setting the value of τ(hand to bat) / τ(ball to bat), since the variability of this ratio was significantly higher. It was concluded that the optical variable tau contains important information for controlling interceptive actions. Namely, it afforded predictive information and, at the same time, was used in controlling deceleration of the hand.*

6.1 Introduction

Many perceptuo-motor actions require controlling velocity of approach to an object or destination, as when a pigeon lands on a perch (Lee, *et al.*, 1992a), when a bat flies to an aperture (Lee, *et al.*, 1992b) or when a driver stops behind another vehicle (Lee, 1976). In the present study we analysed CP children's and nursery children's striking actions in terms of a general theory of control of velocity of approach. The theory was described in detail in Chapters 3 & 8 (Appendix).

Controlling interceptive actions

Applying the theory of control of velocity of approach to the control of interceptive actions, consider the task of hitting an accelerating ball with a bat. Because the ball is accelerating, the tau-margin to the surface of the bat is, strictly speaking, an overestimate of the time-to-contact with the bat. However, with normal accelerations the overestimate is negligibly small over the last 300 msec before contact (Lee et al., 1983). Experiments indicate that the tau-margin is indeed used in timing actions during accelerative approaches (Lee & Reddish, 1981; Sidaway *et al.*, 1989; Lee *et al.* 1983). Particularly relevant for the present study are the interceptive timing experiments carried out on Cerebral Palsied children and normal children (Chapter 5). In these experiments it was established that both groups of children used a certain value of τball rather than a certain value of distance, velocity or time when initiating striking actions to hit an approaching ball.

Analysing the same data it is hypothesized that, based on the theory a constant tau-dot approach, when actually striking an accelerating ball the children keep the rate of change of tau of their moving arm equal to the rate of change of tau of the approaching ball. The question is: How is this relationship regulated so that the ball is hit at the right time?

Perceptuo-motor control of such a task might seem to require complex neural computation, in this case based on registering the arm's and the ball's position, velocity, acceleration, rate of change of acceleration and so on. The theory described in Chapter 3 & 8, however, indicates a simpler procedure: gear the movement of the hand to that of the ball so that it remains constant at value k [= τ(hand to bat)/τ(ball to bat)], where hand is the Y-position coordinate of the wrist LED measured from peak velocity onwards until the bat is hit. Setting k = τ(hand to bat)/τ(ball to bat) would result in τ(hand to bat) decreasing linearly to zero at hand/ball bat contact. It should be noted that k will be greater than 0.5. This is because the task for the

children was not to stop at the bat but to hit the ball off the track with it. Therefore, a *controlled-collision* (hand-bat) procedure is necessary.

Following the above procedure requires registering the rate of change of τ(hand to bat) and τ(ball to bat) simultaneously. If the children follow the above procedure in controlling the interceptive actions, then (1) τ(hand to bat) should decrease linearly to zero with τ(ball to bat), and (2) the slope of this linear relationship should lie between 0.5 and 1.0.

6.2 Method

The experimental data collected in the experiments reported in Chapter 5 were used again in this study. The children sat at a table with a track directly in front of them. A ball was rolled down the track towards the child at three different speeds. The task for the children was to strike a bat with the left and with the right hand separately to intercept the ball and knock it off the track.

Measures

Selspot measures

On each trial, the Selspot system scanned the image of infrared light emitting diodes every 3ms and digitized their (X,Y) coordinates. A computer recorded the coordinates at a sample rate of 62Hz. From the computer records, the Y-position coordinates of the wrist LED were used. These coordinates were measured from the start of deceleration onwards until the bat was hit. The resulting time series Y were smoothed with a second order recursive Butterworth filter (cut-off 8Hz), differentiated to give Y'and τ(Y) = (Y-Ymax/Y') was calculated.

Video measures

To measure the consecutive ball positions during its approach to the striking place the same video analyses were used as in Chapter 5. For each of the three ball speeds ten trials of the ball rolling down the slope were recorded from the side. The smoothed position data of the ten trials, in each of the three different ball speeds were then plotted against time at 0.02 secs and fitted with the best possible regression line. This meant a second order polynomial regression line (mean R^2=0.999 across velocity/ trials). The mean equations of these ten regression lines at each ball speed were then used to obtain the values of τ(ball to bat) at ball speed 1, 2, and 3.

To test the experimental hypothesis, for each trial the τ(hand to bat) data series was plotted against the τ(ball to bat) data series.

6.3 Results

Test of constant ratio τ(hand to bat) / τ(ball to bat) hypothesis

The hypothesis predicts that, during final approach (i.e. the time series data from peak velocity to contact with the bat), the τ(hand to bat) will decrease linearly to zero with τ(ball to bat) at a rate between 0.5 and 1.0. Thus the plot of τ(hand to bat) against τ(ball to bat) should be linear.

Figure 1 presents the plots of τ(hand to bat) against τ(ball to bat) for separate hitting movements at the three different ball speeds, together with the means and standard deviations of the linear regression coefficients, for the CP children's affected/non-affected hand and the nursery children's non-dominant/dominant hand.

(Fig. 1a)

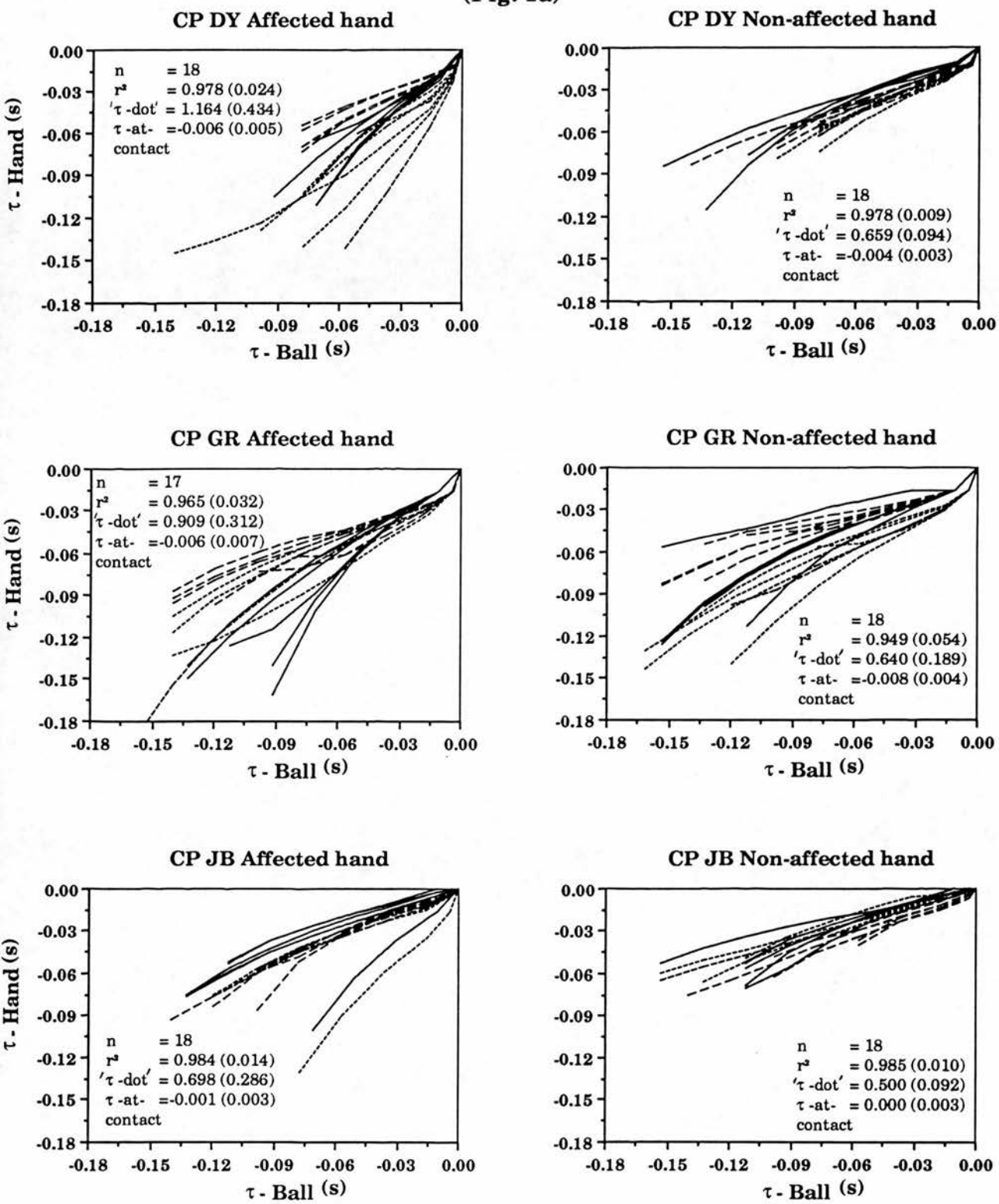
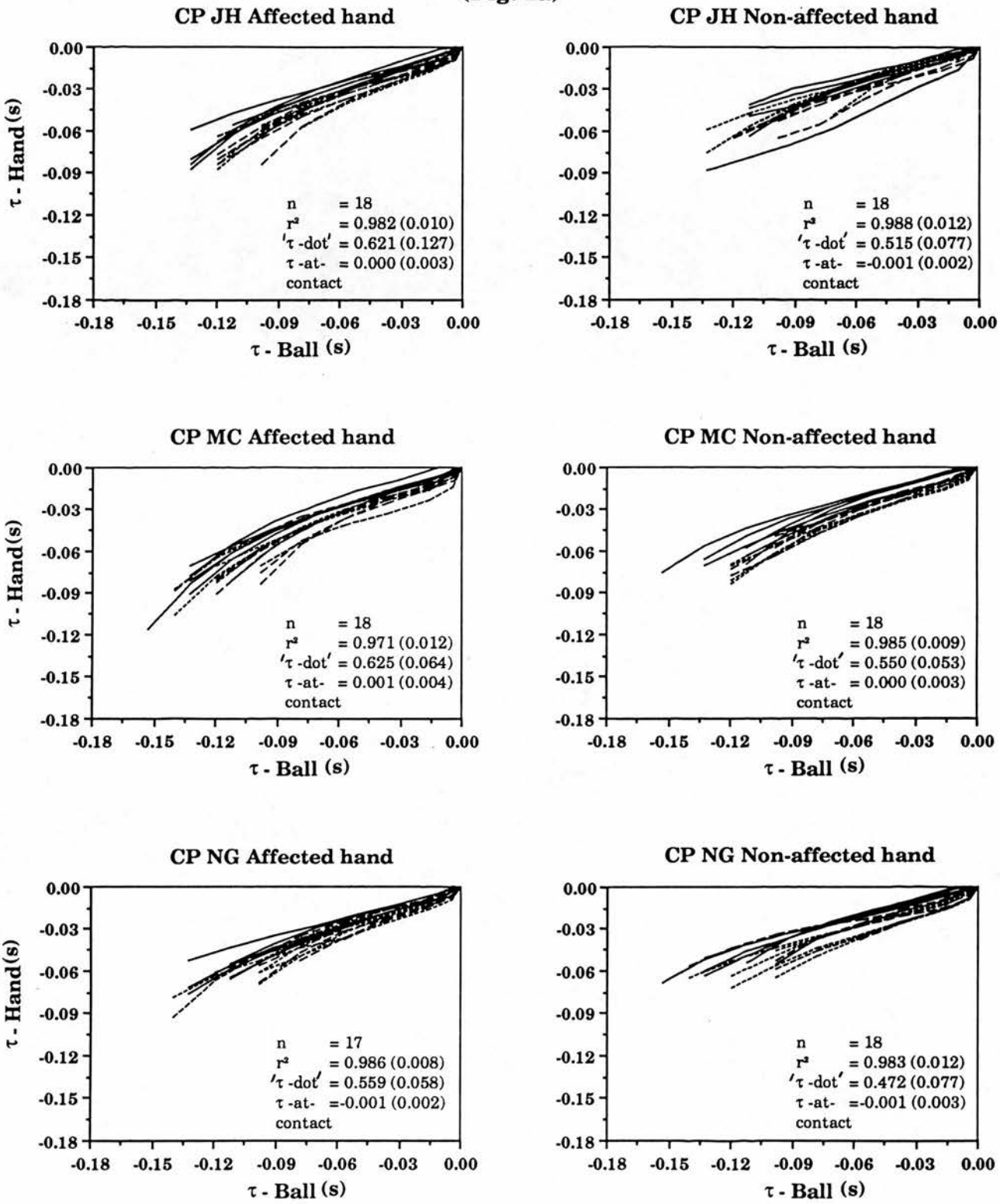


Figure 1a-b. Showing that the CP children (1a) and nursery children (1b) with both hands kept the ratio τ(hand to bat) / τ(ball to bat) closely constant during deceleration to ball / hand bat contact. Solid lines: plots for individual hitting movements at ball speed 1; dashed lines: plots for individual hitting movements at ball speed 2; dotted lines: plots for individual hitting movements at ball speed 3. (continues)

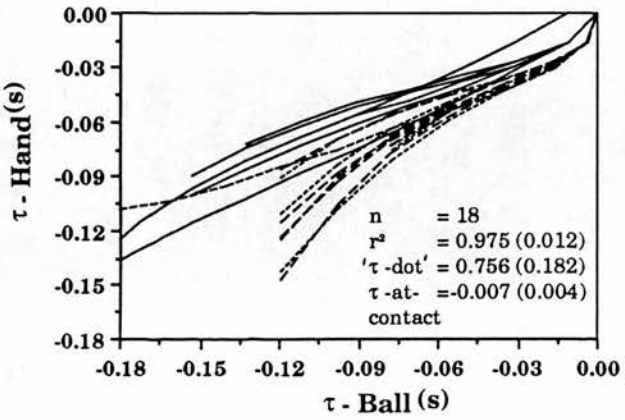
(Fig. 1a)



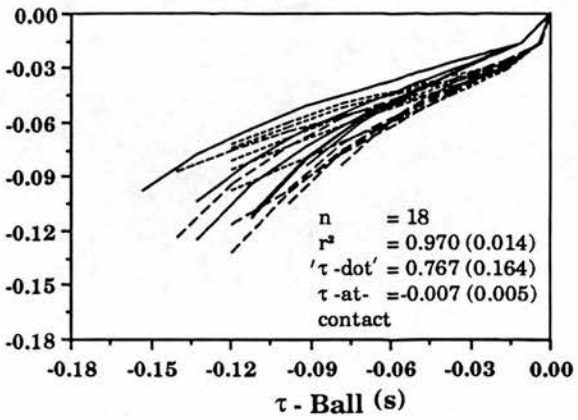
(continued) Means (standard deviations) of linear regression coefficients of τ(hand to bat) on τ(ball to bat) are given in each panel. r^2 values approaching unity indicate linearity - i.e., the rate of change of τ(hand to bat) with respect to τ(ball to bat), rather than to 'absolute' time, is kept constant. In other words, τ(ball to bat) acts as a clock for governing the movement of the hand.

(Fig. 1b)

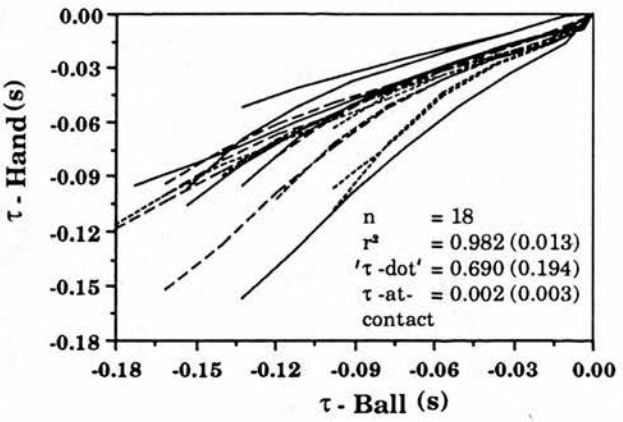
Nurs. An Non-dominant hand



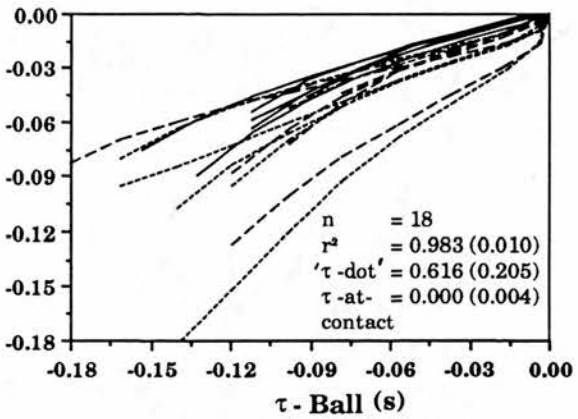
Nurs. An Dominant hand



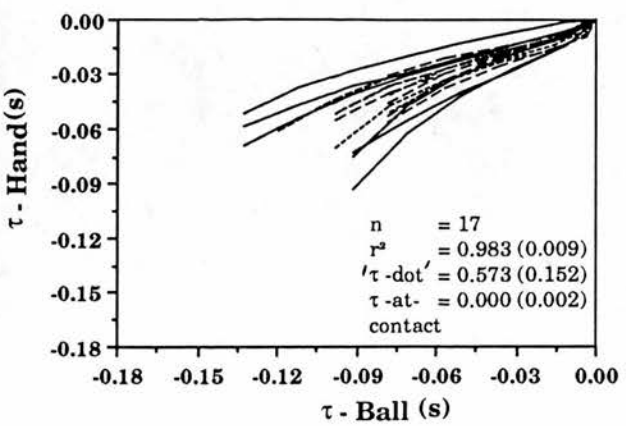
Nurs. Gi Non-dominant hand



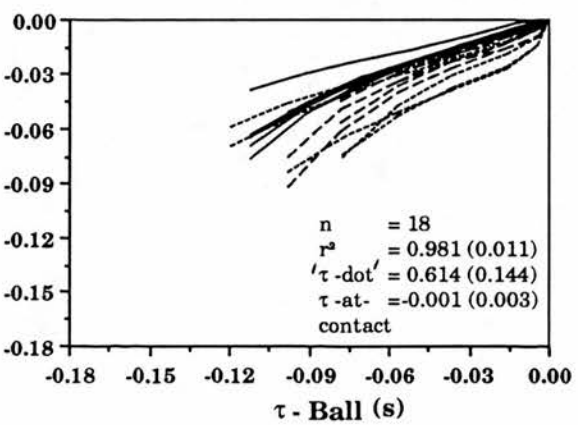
Nurs. Gi Dominant hand



Nurs. Ja Non-dominant hand

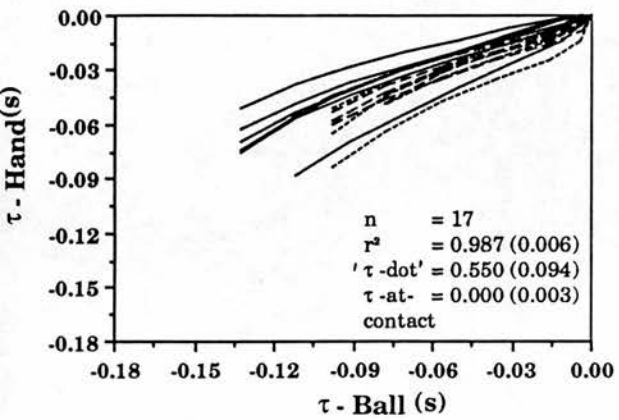


Nurs. Ja Dominant hand

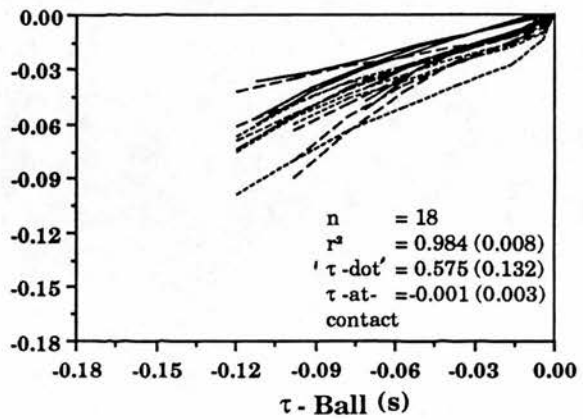


(Fig. 1b)

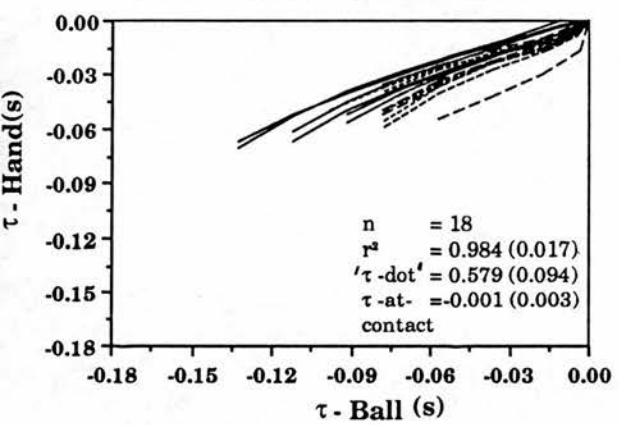
Nurs. Jo Non-dominant hand



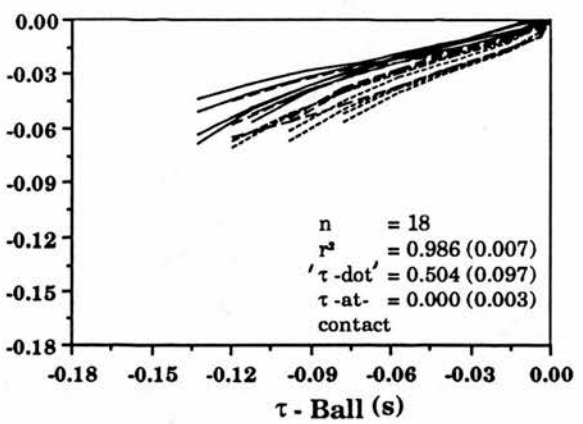
Nurs. Jo Dominant hand



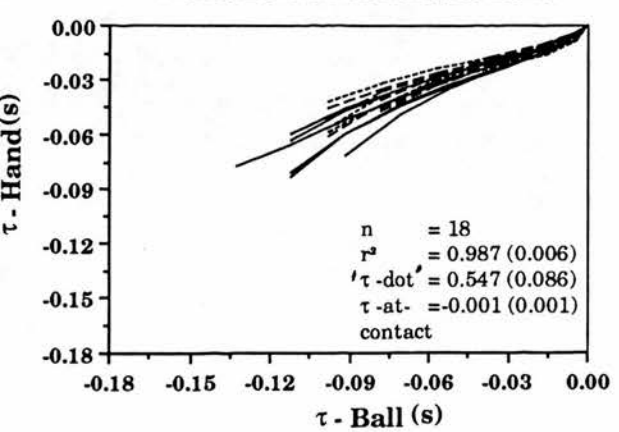
Nurs. Ka Non-dominant hand



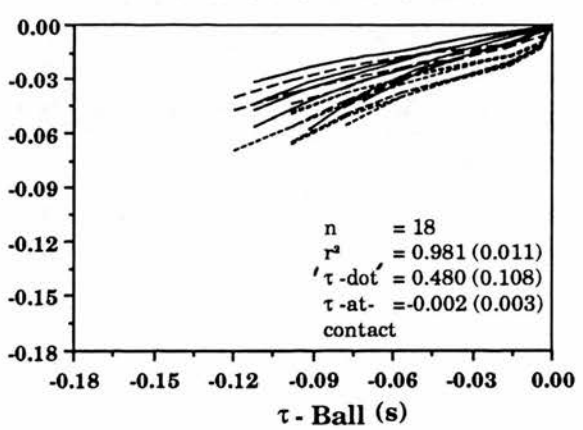
Nurs. Ka Dominant hand



Nurs. Lu Non-dominant hand



Nurs. Lu Dominant hand



Both the CP children and the nursery children behaved similarly. In the CP group, the mean (sd) values of r^2 were 0.978 (0.008) for the affected hand and 0.978 (0.015) for the non-affected hand (Fig. 1a). In the nursery group these values were slightly (but not significantly, $p > 0.2$) higher namely 0.983 (0.004) for the non-dominant hand and 0.981 (0.006) for the dominant hand (Fig. 1b). The means are very close to a value of 1.0 representing perfect linearity. The data therefore strongly support the constant τ(hand to bat)/τ(ball to bat) hypothesis.

The mean values of the ratio τ(hand to bat)/τ(ball to bat) (the linear regression slopes) were 0.763 (0.231) for the CP children's affected hand and 0.556 (0.077) for the non-affected hand. For the nursery children these values were 0.616 (0.086) for the non-dominant hand and 0.593 (0.102) for the dominant hand.

All mean regression slope values are significantly less than 1.0 ($p < .05$, affected hands; $p < .0001$, non-affected hands; $p < .0001$, non-dominant hands; $p < .0001$, dominant hands, t-tests). These values are also greater than 0.5 ($p < .05$, affected hands; $p < .05$, non-dominant hands; $p < .05$, dominant hands, t-test) except for the CP children's non-affected hands which were not significantly different from 0.5 ($p > .05$). This means that, in general, the children were decelerating towards ball/hand bat contact on a *controlled collision* course (see Fig. 1b in Chapter 3).

In addition, a mixed measures ANOVA (Group x Hand) was carried out on the linear regression slopes. This analysis showed a significant two way interaction effect of Group x Hand ($F(1,10) = 6.8$, $p < 0.05$). Further observation of the individual means revealed that the linear regression slopes for the affected hands were significantly higher than those for the non-affected hands in the CP group only.

The intra-individual variability for the affected hands was also higher. An ANOVA carried out on the standard deviations of τ(hand to bat)/τ(ball to bat) (the linear regression slopes) showed a significant two way interaction of Group x Hand ($F(1,10) = 5.06$, $p < 0.05$). Observation of the individual means indicated that the standard deviations of the linear regression slopes for the affected hands were significantly higher than those for the non-affected hands in the CP group only.

6.4 Summary & Discussion

The data support the hypothesis that both the CP children and the nursery children regulate deceleration of the hand by keeping constant the dimensionless quantity τ(hand to bat)/τ(ball to bat), i.e., the rate of change of τ(hand to bat) with respect to τ(ball to bat), rather than to 'absolute' time. In other words, τ(ball to bat) acts as an 'environmental clock' for governing the movement of the hand. Thus, the children appear to control braking in a similar way as birds (Lee, *et al.* 1991), bats (Lee, *et al.* 1992b), pigeons (Lee, *et al* 1992a), and adults (Lee, 1976) control braking (see also Chapter 3).

The results also showed that τ(hand to bat)/τ(ball to bat) was kept constant at a value between 0.5 and 1.0, indicating that the children were decelerating towards ball/hand bat contact on a *controlled collision* course.

The variability of the regression slopes for the affected hands was significantly higher than that for the non-affected hands in the CP group only. What does this indicate? The procedure of regulating deceleration of the hand so that τ(hand to bat)/τ(ball to bat) decreases linearly to zero at ball/hand bat contact has two components: (1) setting the rate of change τ(hand to bat) equal to the rate of change of τ(ball to bat), and then (2) keeping τ′(hand to bat) constant. The strength of the linear regression of τ(hand to bat)/τ(ball to bat), as indexed by the r^2 values, was as high for the affected hand as for the non-affected, non-dominant and dominant hand (Fig. 1a-b). Thus, it does not appear that the affected hand of the CP children was handicapped in keeping τ′(hand to bat) constant. However, the affected hands were clearly handicapped in setting the value of τ′(hand to bat), since the variability of τ(hand to bat)/τ(ball to bat) was significantly higher (Fig. 1a-b). These values were also significantly higher for the affected hands, indicating that the CP children were decelerating their affected hand significantly harder towards contact with the bat than the non-

affected, non-dominant, and dominant hands. This could indicate less ability for precise movement control since braking was carried out more vigorously.

Apart from its use in regulating deceleration, the tau function of distance to a surface, $\tau(x)$, is valuable information for controlling timing during approach, as was shown, using the same children, in Chapter 5. In Chapter 5, it was shown that $\tau(x)$ was used not only under constant approach velocity, where it gives a precise measure of time-to-contact, but also under changing velocity, where $\tau(x)$ provides a first-order estimate of time-to-contact.

Thus, from the results of both Chapter 5 and the present Chapter it can be concluded that the whole act of striking the ball with the hand at the right time was governed by the same underlying principle namely that of tau and its time derivative tau-dot. Initiation of the three striking actions Hand Starts, Hand Accelerates, and Hand Decelerates was governed by the initiation variable τball (see Chapter 5).

Deceleration of the hand towards ball/bat hand contact was regulated so as to keep the rate of change of deceleration constant at a particular value of τ(hand to bat)/ τ(ball to bat). It remains to be seen whether acceleration of the hand and the changing point between acceleration and deceleration of the hand during the entire striking actions is regulated in similar ways. These questions suggest a potentially fruitful set of new analyses.

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Chapter 7

Summary & Discussion

7.1 The Logic of Relationships

This thesis presented an action approach to human movement that emphasizes the implicate relationships between a moving organism and the environment. The ecological concept of affordances provided a useful framework for designing experiments which assume such relationships and also proved a valuable tool for explicating these implicate relationships in more detail. In this concluding Chapter the most important results of the experimental work reported in this thesis will be summarized and discussed in relation to the concept of affordances and in relation to the more general action approach to human movement.

In Chapter 2, it was investigated whether Cerebral Palsied children pronated and supinated their forearms further on a concrete bang-the-drum task than on an abstract move-as-far-as-you-can task. This experiment was included to determine the difference between producing movements which are part and parcel of an action process as opposed to producing bodily movements for their own sake. The results showed that the children rotated the forearm further in the concrete bang-the-drum task.

Thus, movement *outcome*, i.e. range of movement, was significantly larger when the pronation and supination movements were carried out as an integral part of an action process. In this way, the children were provided with a functional context which was of direct significance to them. In such a context the rotation movements

could be related to objects in the environment and the children were exposed to additional visual, auditory and tactile perceptual information about their relation to the drum. It was concluded that, because the CP children performed better on the concrete task than on the abstract task, concrete tasks need to be used in addition to abstract tasks in assessments of limb movement in order to obtain a full picture of the child's ability.

However, not only movement outcome was different between the abstract and the concrete rotation tasks but the underlying movement kinematics were different too. This was shown in Chapter 4. Although the form of the pro/supination movements in the abstract and concrete task looked indistinguishable by eye, detailed analyses of pronation and supination movements revealed that, at least, three different kinematic variables were significantly different between the two experimental tasks.

Analyses of velocity profiles showed that in the concrete task the acceleration phase was longer than in the abstract task. Observation of the phase plane trajectories indicated that especially supination movements in the abstract rotation task reached greater range of velocity, and that range of pro/supination movements was larger in the concrete rotation task. Analyses of angular-tau revealed that the child, in both rotation tasks, used a *controlled collision* procedure. Angular-tau deceased linearly to zero towards contact with the extreme pro/supination position at a rate between 0.5 and 1.0. However, angular-tau dot, the mean of slopes of the linear regression lines, was significantly higher for pro/supination movements in the concrete rotation task.

On the basis of these differences it was concluded that varying the amount of perceptual information in the abstract and concrete rotation tasks influenced movement control in Cerebral Palsy. This implies that therapies for overcoming motor disorder should not only concentrate on promoting movement patterns which

may or may not transfer to perceptuo-motor activities of daily life, but should also concentrate on these activities directly. In order to learn a certain perceptuo-motor task appropriately, all information relevant to the performance of that task needs to be present during the acquisition of the task (Bootsma, 1988; Fowler & Turvey, 1978; Saltzman & Kelso, 1987).

However, it goes without saying that the interpretation of the results obtained in Chapter 4 are still speculative because they are based on the performance of only one subject. Replication on a larger scale is needed. At least, the tentative conclusions, drawn from the differences in kinematic variables between the abstract and the concrete task, can serve as hypotheses for such replications.

Interceptive timing actions of CP children and nursery children were examined in Chapter 5. This was to determine what source of perceptual information these children used to control their hands to strike an approaching ball. The results suggested that both groups of children used the optical variable τ(ball) for initiating and guiding the striking actions. The affected hands of the CP children always initiated the striking actions at a significant larger value of tau. However, although the affected hand started the striking actions much earlier than the non-affected hand, these preparatory actions were nevertheless part of a highly organised striking action, as was shown in the results. This supported the hypothesis that the optic variables specifying τ(ball) 'contain' important body and action scaled perceptual information.

The importance of body/action scaled perceptual information for specifying τ(ball) was also shown by the fact that in the "button-press" condition timing behaviour was much more variable. Instead of simplifying the task by eliminating the movement component from the timing action, the "button-press" condition became more difficult because at the same time body/action scaled information was no longer available.

How can these results be understood in relation to the action approach of human movement outlined in the introduction? In the opening Chapter of this thesis, the active role of the body in perceptuo-motor control was emphasized. It was argued that the environment is always perceived in relation to the observer, and that perceptual information to specify the environment always points two ways, to the environment as well as to the observer (Gibson, 1979). The results of Chapter 5 support this hypothesis. Just as people perceive climbability of a stairway in terms of their leg-lengths (Warren, 1984), and passability through apertures in terms of their shoulder widths (Warren & Whang, 1987), the cerebral palsied children perceived the approaching ball in terms of the affectedness of the arms.

How might such a relational view be achieved? In the process of learning and in the course of development bodily characteristics, which are revealed through action, have been incorporated in a stable bodily frame of reference for action. Such a bodily frame of reference for action requires 'knowledge' of the characteristics, capabilities and limitations of one's own body (Van der Weel, 1991).

We all have experienced this process of incorporation, namely, when learning new perceptuo-motor skills. For instance, extensions of the human body such as tennis racquets, ski's, golf clubs, dentures and artificial limbs, first have to be incorporated into our habitual frame of reference, before we can use them to their full potential. At first, we experience those instruments as unmanageable barriers between ourselves and the environment (Zaner, 1971). However, once incorporated in our 'bodily' frame of reference, they increase our action possibilities considerably, and are almost considered own body parts.

An experiment by Van der Meer and Van der Weel (in press) examined how in infancy a stable frame of reference may be established. Spontaneous arm movements were investigated in newborn babies. Weights were attached to the babies' wrists, effectively pulling the arms away from the face in the direction of the toes. The results showed that the babies managed to keep the arm they had their face turned to in their

field of view, despite the addition of weights - but only if they could see that arm. It was concluded that early arm and hand movements play an exploratory role in the acquisition of prehension. As infants wave their arms and hands while supine, they are learning about their own body and its dimensions through vision, as well as about the consequences of their movements on the environment.

The hypothesis that perceptual information for controlling action is perceived not in centimetres and seconds or in any other arbitrary unit of measure, but, is perceived in terms of the type and magnitude of action that is to be applied to them, was tested in Chapter 6. In this Chapter the interceptive timing actions of CP and nursery children were analysed in more detail. It was investigated how these children regulated deceleration of the hand during the final approach before contact with the bat. The results indicated that both groups of children controlled deceleration of the hand by keeping constant the ratio τ(hand to bat)/τ(ball to bat) at a value between 0.5 and 1.0. It was concluded that the children regulated their striking actions to 'relative' time rather than to 'absolute' time. Namely, the optical variable τ(ball to bat) acted as some sort of 'environmental clock' for governing the movement of the hand towards the bat.

The results of Chapter 6 also showed that the affected hands of the CP children were clearly handicapped in setting the value of τ(hand to bat)/τ(ball to bat). These results provided a good example of how, according to an action approach of human movement, action processes can be analysed and understood in considerable detail without separating them into their constituent, externally related, bodily movements. In Chapter 1 of this thesis, it was argued that an adequate description of an affordance always entails specifying the implicate order of the relationships between the organism and the environment and explaining the implicate order of relationships in terms of and *explicate* order to provide more detailed information about the ecosystem. This is exactly how the results of Chapter 6 were obtained.

In the special affordance tau an intimate relationship between an organism and the environment is reflected, namely, the tau function is a property of a continuous changing optic flow field in which information about the environment *and* the movements of the observer are directly specified (Gibson, 1966; Lee 1976; see also Chapter 3). From the implicate order of relationships between the organism and the environment relatively autonomous values of τ(hand to bat)/τ(ball to bat) were explicated to characterize the organism/environment fit in more detail. In this way the fact that, for instance, the affected hands were clearly handicapped in setting the value of τ(hand to bat)/τ(ball to bat) could be revealed.

Therefore, future research on perceptuo-motor control in Cerebral Palsy should utilize this method in order to find relational, but detailed information about the children's handicap. This is exactly what is planned for future research. The aims of the research project are to devise effective therapy and assessment techniques for movement disorder in the CP child which require relational, in-depth measures of the child's disability. Current assessment mainly uses measures of surface behaviour, but these measures cannot reveal the underlying principles of movement disorder which therapy needs to address. Particular attention will be directed to prospective control of speed of approach to a goal in perceptuo-motor tasks such as stabilizing gaze during movement, interceptive timing, pronating and supinating the forearm, coupling visual and non-visual information and reaching and grasping. A theoretical framework for these future experiments was outlined in Chapters 1, 3, & 8 (Appendix) and tested experimentally in Chapters 4, 5 & 6 of this thesis, as well as in other literature (Lee *et al.*, 1991, 1992a,b,c).

If I could sum up the principal burden of this thesis, it would be as follows: an adequate integration of anthropology within a wider field of psychology requires that the study of movement control be subsumed under the study of action processes. However, the traditional, dominant paradigm of the psychology of human movement

has no place for action processes. The most urgent task for kin-anthropologists (Tamboer, 1985) is to overcome the underlying separation of organism and environment. The approach I have sketched out here is one that attempts to do just that. I have tried to show that a theory of movement control can be encompassed within a more general theory of action processes, without compromising the active and central role of the organism. To arrive at this conception of action processes, however, we need a new theory of human movement. It must be a theory that asserts the primacy of processes over events, of relationships over entities, and of learning and development over structure. We stand in a desperate need of a psychology of human movement that would recognise that "it is not the bits and pieces, of abstract entities that matter but the evolving organism-environment system as a whole" (Leach, 1967). Only with such a theory can we begin to understand 'movement control'. But to realize a psychology of human movement of this kind we must reject the logic of bits and pieces, of abstract entities, and install in its stead a *logic of relationships*.

7.2 References

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Chapter 8 (Appendix)

The Theory of Control of (Speed of) Approach

(The general theory of control of speed of approach is also outlined in: Lee, D.N., Van der Weel, F.R., Hitchcock, T., Matejowsky, E. & Pettigrew, J.D. (1992b). Common principle of guidance by echolocation and vision. *Journal of Comparative Physiology,* in press.)

8.1 Introduction

The theory, which applies to approach along any dimension, will be illustrated by linear approach of an animal to a surface (Fig. 1a). The point on the surface being approached is considered the origin O and at time t the animal A has coordinate x (arbitrarily taken to be less than zero) and is approaching O at velocity x′ and acceleration x″ (x′ and x″ denote the first and second derivatives of x with respect to time).

The *tau function* of x is defined as x divided by its rate of change over time (x′). In symbols:

$$\tau(x) = x/x' \quad \text{(A1)}$$

$-\tau(x)$ is the time it would take the animal to reach O if it were to continue at a constant approach velocity x′.

The rate of change of $\tau(x)$ ($=\tau'(x)$) provides information for controlling velocity of approach. To see this, we differentiate Eq. (A1) with respect to time, obtaining:

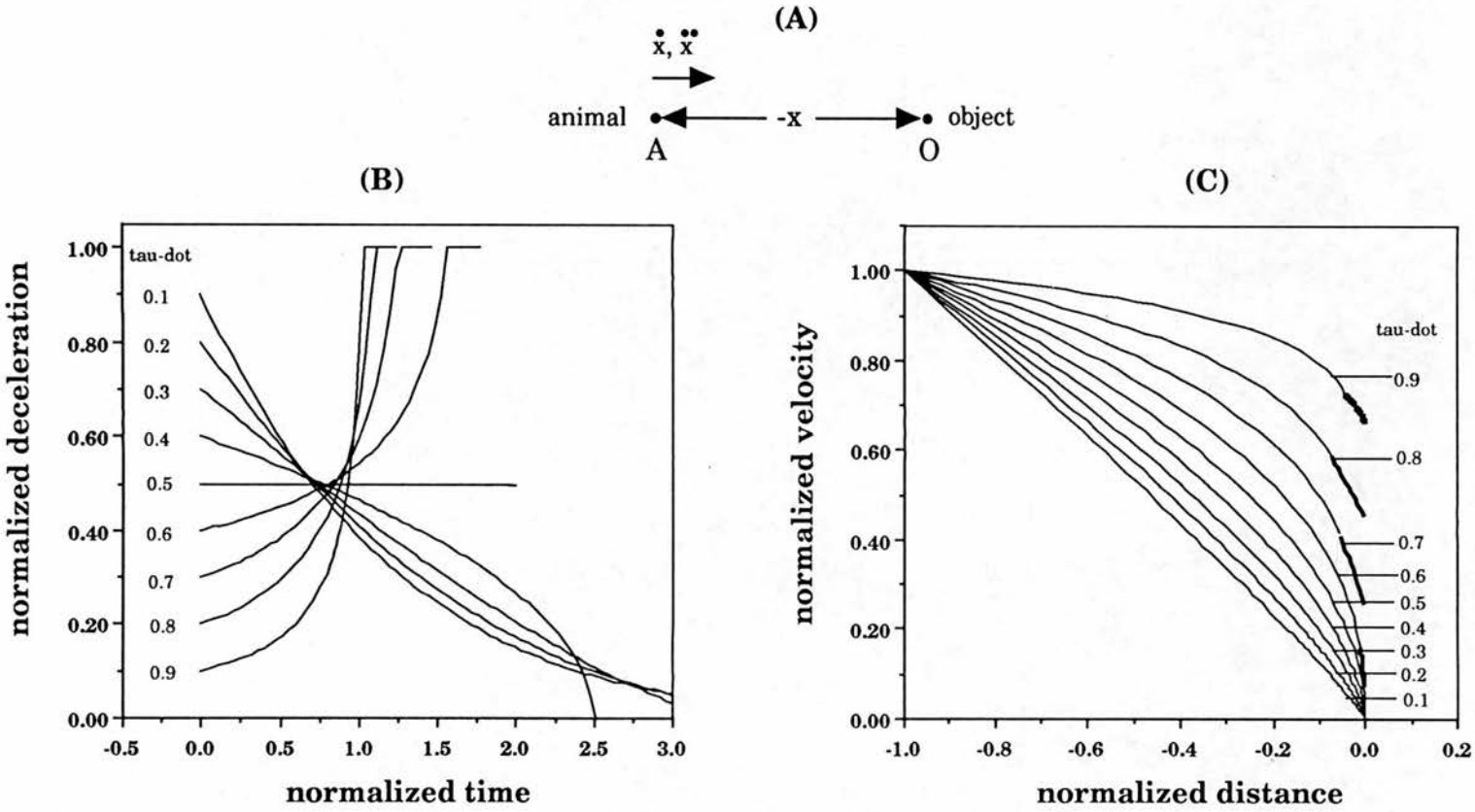

Figure 1. Theory of control of (speed of) approach. (A) At time t animal has coordinate x (<0) and is approaching surface with velocity x′ and acceleration x′′ (x′ = dx/dt, x′′ = d^2x/dt^2). Tau function of x = τ(x) = x/x′. Tau-dot = rate of rate of change of τ(x) = τ′(x). (B) and (C) Kinematic profiles when approaching surface and braking so that τ′(x) remains constant at the different values shown. If 0 < τ′(x) < 0.5, deceleration monotonically decreases (curves for τ′(x) (= tau-dot) = 0.1-0.4 in (B)) and object is just reached (corresponding curves in (C)). If τ′(x) = 0.5, deceleration is constant (horizontal line in (B)) and surface just reached (τ′(x) = 0.5 line in (C)). If 0.5 < τ′(x) < 1, deceleration increases monotonically, as shown by curves for τ′(x) (=tau-dot) = 0.6-0.9 in (B); thick lines at top of curves correspond to reaching a deceleration ceiling. Corresponding curves in (C) show how velocity decreases.

$$\tau'(x) = 1 - xx''/x'^2 \qquad (A2)$$

It is clear from this equation that, during approach to O (i.e., $x<0$ and $x'>0$):

$\tau'(x)>1$ implies animal accelerating (i.e., $x'' > 0$) and time-to-contact $< -\tau(x)$;

$\tau'(x)=1$ implies animal moving at constant velocity (i.e., $x'' = 0$) and time-to-contact $= -\tau(x)$;

$\tau'(x)<1$ implies animal decelerating (i.e., $x'' < 0$) and time-to-contact $> -\tau(x)$.

8.2 Constant Deceleration Approach

Suppose the animal is decelerating towards O with *constant* deceleration $-x''$ (>0). Then the stopping distance from approach velocity x' will be $-x'^2/(2x'')$. Therefore the animal will stop short of O providing $-x'^2/(2x'') < -x$, i.e., providing $xx''/x'^2 > 0.5$. Thus, applying Eq. (A2), the condition for stopping short is

$$\tau'(x) < 0.5 \quad (A3)$$

If $\tau'(x) = 0.5$, the animal will stop *at* O.

Thus, though control of braking might appear to require information about the current distance from the destination, and about the current velocity and deceleration of approach, none of this information is strictly necessary. To avoid collision it is sufficient to register the value of $\tau'(x)$, adjust braking so that $\tau'(x) \leq 0.5$ and then keep braking constant. Application of this constant-braking procedure will necessarily result in $\tau'(x)$ getting progressively smaller over time and the animal stopping short of the destination (except if $\tau'(x) = 0.5$ when $\tau'(x)$ will stay constant and the animal will stop at the destination). Conversely, if deceleration is kept constant when $\tau'(x)$ is greater than 0.5, then $\tau'(x)$ will get progressively larger over time and the animal will collide with the destination.

8.3 Constant $\tau'(x)$ approach: stopping at a destination

To *stop at* a destination it is sufficient to adjust braking so that $\tau'(x)$ stays constant at a value k, $0 < k \leq 0.5$. The equations of motion resulting from following this procedure are obtained by integrating Eq. (A2) (substituting the constant value k for $\tau'(x)$). The equations of motion are:

$$x/x_0 = (1 + kt/\tau_0)^{(1/k)} \qquad \text{(A4)}$$

$$x'/x_0' = (1 + kt/\tau_0)^{(1/k)-1} \qquad \text{(A5)}$$

$$x''(x_0/x_0'^2) = (1-k)(1 + kt/\tau_0)^{(1/k)-2} \qquad \text{(A6)}$$

where $-x_0$, x_0', $-x_0''$ are, respectively, the animal's distance from the destination and its velocity and deceleration of approach at time t=0. $\tau_0 = x_0/x_0'$.

We assume the animal is moving toward the destination O at time t=0; i.e., $x_0<0$ and $x_0'>0$. Therefore $\tau_0 < 0$. Hence, from Eq. (A4), x/x_0 will decrease over time, i.e., the animal will continue to approach O. (If the animal were moving away at t=0, then

by keeping $\tau'(x) = k$ it would move away from O.) Eqs. (A4-A6) may then be normalized by writing:

normalized distance =

(distance from destination)/(initial distance) = $x_n = x/x_0$;

normalized velocity =

(velocity)/(initial velocity) = $x_n' = x'/ x_0'$;

normalized time =

time/(initial time-to-contact with destination under constant velocity) =

$t_n = -t/\tau_0$;

normalized deceleration =

deceleration / (twice constant deceleration needed to stop at destination) =

$x_n'' = x''(x_0/ x_0'^2)$.

The normalized equations of motion are:

$$x_n = (1 - kt_n)^{(1/k)} \qquad \text{(A7)}$$

$$x_n' = (1 - kt_n)^{(1/k)-1} \qquad \text{(A8)}$$

$$x_n'' = (1-k)(1 - kt_n)^{(1/k)-2} \qquad \text{(A9)}$$

where normalized time to reach destination = 1/k.

Following the "stop-at" procedure of keeping $\tau'(x)$ constant at a value k, $0 < k \leq 0.5$ requires steadily slackening off the brakes as the destination is approached (except for k=0.5 when deceleration is constant). This is because the exponent ((1/k)-2) in Eq. (A9) is positive. How deceleration falls off is shown in Figure 1b by the graph lines, derived from Eq. (A9), for $\tau'(x) = 0.1 - 0.4$. In Figure 1c, the graph lines for $\tau'(x) = 0.1$-0.4, derived from Eqs. (A7 and A8), show how velocity of approach decreases to zero as the destination is approached.

Eqs. (A7-A9) also describe the motion of the animal which would result from keeping $\tau'(x)$ constant at a value k, $0.5 < k < 1$. In this case, the exponent in Eq. (A9) is negative. This means that braking has to get progressively *harder* as the destination is approached. Moreover, stopping at the destination in this way theoretically requires reaching infinite braking force. A realistic procedure - which we will call the *controlled-collision* procedure - is to keep $\tau'(x)$ constant at a value between 0.5 and 1.0 until maximum braking power is reached, and then maintain this braking force. This would result in the animal colliding with the destination but in a controlled way. In Figure 1b, the curves for $\tau'(x) = 0.6$-0.9, derived from Eq. (A9), show how deceleration builds up when following the controlled-collision procedure; the thicker lines at the top of the curves correspond to maintaining, up to collision, a constant maximum normalized deceleration of unity. How velocity of approach decreases as a result of these deceleration patterns is shown by the corresponding curves in Figure 1c.